NASA Contractor Report 159374

NASA-CR-159374
19810006040

EVALUATION OF ATMOSPHERIC DENSITY MODELS AND PRELIMINARY FUNCTIONAL SPECIFICATIONS FOR THE LANGLEY ATMOSPHERIC INFORMATION RETRIEVAL SYSTEM (LAIRS)

T. Lee and D. E. Boland, Jr.

COMPUTER SCIENCES CORPORATION
Silver Spring, Maryland 20910

NASA Contract NAS1-15663
September 1980

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

CSC/TM-80/6240

EVALUATION OF ATMOSPHERIC DENSITY MODELS AND PRELIMINARY FUNCTIONAL SPECIFICATIONS FOR THE LANGLEY ATMOSPHERIC INFORMATION RETRIEVAL SYSTEM (LAIRS)

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

By

COMPUTER SCIENCES CORPORATION

Under

Contract NAS 1-15663

N81-14554

This Page Intentionally Left Blank

ABSTRACT

This document presents the results of an extensive survey and comparative evaluation of current atmosphere and wind models for inclusion in the Langley Atmospheric Information Retrieval System (LAIRS). It includes recommended models for use in LAIRS, estimated accuracies for the recommended models, and functional specifications for the development of LAIRS.

This Page Intentionally Left Blank

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

Table

SECTION 1 - INTRODUCTION

Postflight determination of aerodynamic force coefficients for the Shuttle Orbiter via the Aerodynamic Coefficient Measurement Experiment (ACME) will require independent knowledge of the characteristics of the atmosphere along the Shuttle reentry path.

As a part of the planning for the ACME Program, the NASA Langley Research Center is making arrangements with the Shuttle Project to obtain certain atmosphere measurements near the time and path of each reentry flight. These measurement data, taken from balloons, sounding rockets, aircraft, and ground stations, will be processed by LaRC to determine the needed atmospheric velocity, pressure, temperature, and density along the Shuttle trajectory. Knowledge of the atmosphere's local velocity vector not only will permit the determination of the relative speed, V, but, together with the vehicle attitude, will also make possible the computation of the aerodynamic angle of attack, α, and the sideslip angle, β. Knowledge of thermodynamic properties other than density will define parameters such as the local speed of sound and the viscosity. These parameters will in turn determine the flight Mach number and Reynolds number for correlation of the aerodynamic coefficients with other experimental data.

In support of this activity, an atmospheric data processor, the Langley Atmospheric Information Retrieval System (LAIRS), will be developed for use in the ACME Project. In preparation for the development of LAIRS, Computer Sciences Corporation (CSC) has conducted a survey and comparative evaluation of current lower atmosphere, upper atmosphere, and wind models; recommended models for use in LAIRS;

estimated the expected accuracies of the recommended models, and generated functional specifications for LAIRS. This report contains the results of these studies.

Section 2 discusses the various atmosphere and wind models considered and the models recommended for use in LAIRS. Section 3 discusses diurnal, semidiurnal, and latitudinal variations and presents procedures for fitting temperature, density, pressure, and wind profiles. It also includes a discussion of estimated model accuracies. Section 4 consists of the functional specifications for LAIRS.

The authors wish to acknowledge the direction and assistance of Gloria P. White of CSC, who contributed many helpful suggestions and comments, and the overall guidance of the work by Joseph M. Price of the Langley Research Center.

SECTION 2 - EVALUATION OF ATMOSPHERIC MODELS

Currently available atmospheric models are reviewed in this section. Atmospheric models that are appropriate for the lower part of the atmosphere are discussed in Section 2.1 and those for the upper part of the atmosphere are discussed in Section 2.2, while Section 2.3 deals with wind modeling. In each case, recommendations are made for specific models to be implemented in the Langley Atmospheric Information Retrieval System (LAIRS).

2.1 LOWER ATMOSPHERE MODELS

The Earth's atmosphere from ground level up to approximately 100 kilometers is referred to as the lower atmosphere in this report. This portion of the atmosphere consists of several layers with different physical properties. The troposphere, which is the region nearest the Earth's surface, exhibits a more or less uniform decrease of temperature with altitude and is bounded by the next layer, the stratosphere, at an altitude of about 10 kilometers. The troposphere is the domain of weather and is in convective equilibrium with the Sun-warmed surface of the Earth. The stratosphere has about the same vertical dimension as the troposphere and has a nominally constant temperature. The stratosphere is known to have mostly horizontal winds. The mesosphere lies above the stratosphere. It is the region containing the first temperature maximum and is bounded from above by the major temperature minimum, which is found near an altitude of 85 kilometers. The thermosphere covers the entire atmosphere above the mesosphere and is characterized as a region of rising temperature. A typical temperature-altitude profile is shown in Figure 2-1.

If the atmosphere were macroscopically motionless for a sufficiently long time, it would show a decrease in mean

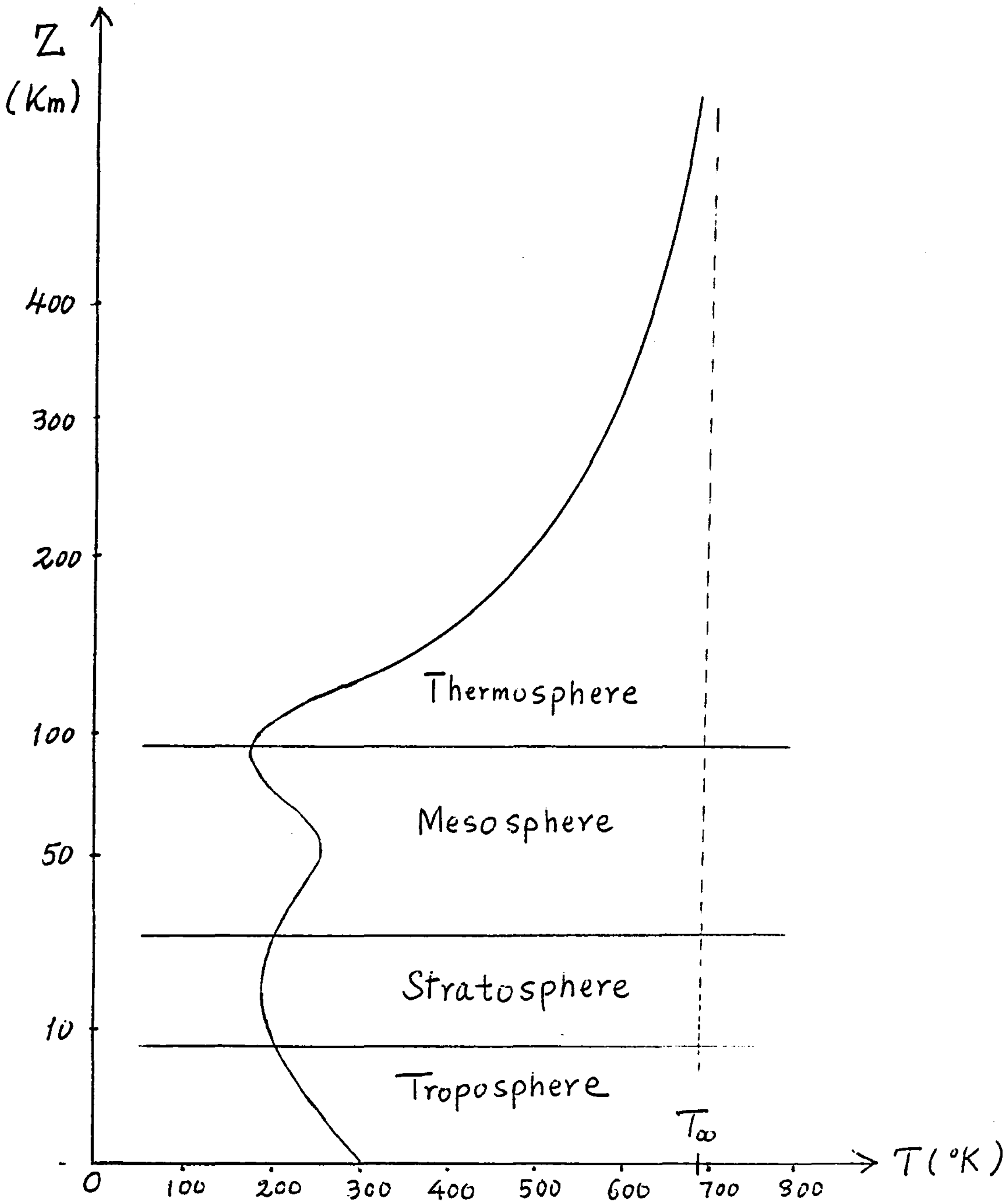

Figure 2-1. Typical Temperature Profile

molecular weight with altitude, with the lighter species having separated from the heavier species by the process of molecular diffusion. Such a process is not observed in the Earth's atmosphere until an altitude of about 100 kilometers is reached; up to this altitude, the mean molecular weight remains approximately constant. This comes about because the Earth's atmosphere is not motionless on a macroscopic scale, but is continually mixed by atmospheric turbulence and large-scale circulation. The beginning of diffusive separation at altitudes near 100 kilometers does not mean that there are no winds to cause turbulence and mixing above these altitudes, but rather that at such low densities molecular diffusion rates are much greater than the wind-induced mixing rates.

The lower atmosphere is thus assumed to have a uniform composition, in the sense of having a constant mean molecular weight. It is also assumed that the air behaves as if it were a perfect gas obeying the perfect gas law:

$$p = \rho R^* T / M \qquad (2\text{-}1)$$

where

p	=	total pressure
ρ	=	total density
T	=	absolute temperature
M	=	mean molecular weight
R*	=	universal gas constant

Within the height region of complete mixing, the atmosphere is further assumed to satisfy the hydrostatic equation, i.e.,

$$dp = -\rho g \, dZ \qquad (2\text{-}2)$$

where

g = acceleration of gravity

Z = geometric altitude

Equations (2-1) and (2-2) can be combined to obtain the integral form of the barometric equation:

$$p = p_0 \exp\left(-\int_{Z_0}^{Z} \frac{1}{H_p}\, dZ\right) \tag{2-3}$$

where

p = pressure at Z

p_0 = pressure at Z_0

H_p = R^*T/Mg

The quantity H_p is referred to as the pressure scale height. The total atmospheric density ρ can be obtained from Equations (2-1) and (2-3):

$$\rho = \rho_0 \frac{T_0}{T} \exp\left(-\int_{Z_0}^{Z} \frac{1}{H_p}\, dZ\right) \tag{2-4}$$

where

$$\rho_0 = M P_0 / R^* T_0$$

The density scale height, H_ρ, can similarly be defined through the following equation:

$$\rho \equiv \rho_0 \exp\left(-\int_{Z_0}^{Z} \frac{1}{H_\rho}\, dZ\right) \tag{2-5}$$

The density scale height and the pressure scale height are related through the following equation:

$$H_\rho = H_p \Big/ \left[1 + \frac{R^*}{Mg} \frac{dT}{dZ} \right] \tag{2-6}$$

where M is treated as a constant.

The following atmosphere models that are currently available were developed using the assumptions discussed above:

1. ARDC Model Atmosphere 1959 (ARDC 1959)
2. U.S. Standard Atmosphere 1962 (USSA 1962)
3. Cospar International Reference Atmosphere 1965 (CIRA 1965)
4. Cospar International Reference Atmosphere 1972 (CIRA 1972)
5. Goddard Institute for Space Studies 1974 Atmosphere (GISS 1974)
6. The Edwards Air Force Base Reference Atmosphere (ERA 1975)
7. U.S. Standard Atmosphere 1976 (USSA 1976)

These models are discussed in the following section.

2.1.1 EVALUATION OF AVAILABLE MODELS

Atmospheric models are often described in terms of the molecular-scale temperature, T_M, and the geopotential height, H. The relation between T_M and T, the ordinary kinetic temperature, is given by

$$T_M = \frac{M_o}{M} T \tag{2-7}$$

where $M = M(Z)$ = mean molecular weight of the atmosphere at height Z.

$M_0 = M(0)$

Since M remains practically unchanged up to about 100 kilometers, T_M and T are essentially the same for the lower atmosphere and begin to deviate from each other above 100 kilometers. The geopotential height, H, is defined in terms of the geometric height, Z, as follows:

$$H = \int_0^Z \frac{g(Z)}{g_0} dZ \qquad (2\text{-}8)$$

where Z = geometric height measured from mean sea level

$g(Z)$ = acceleration of gravity at Z

H = geopotential height

$g_0 = g(0)$ = acceleration of gravity at $Z=0$

The inverse-square law of gravitation provides an expression for $g(Z)$ with sufficient accuracy for most model-atmosphere computations as follows:

$$g(Z) = g_0 \left(\frac{r_0}{r_0 + Z} \right)^2 \qquad (2\text{-}9)$$

where r_0 is the effective radius of the Earth at a particular latitude. Using Equation (2-9) in Equation (2-8), an approximate relation between H and Z can be obtained:

$$H = \frac{r_0 Z}{r_0 + Z} \tag{2-10}$$

The major advantage of using T_M instead of T is that it combines the variable portion of M with the variable T into a single new variable. Similarly, combining the variable portion of g with Z forms the new variable H.

Among the available lower atmosphere models, the ARDC 1959 (Reference 1), USSA 1962 (Reference 2), and USSA 1976 (Reference 3) models were formulated in terms of the molecular-scale temperature and the geopotential altitude.

2.1.1.1 The ARDC 1959 Model

In the ARDC 1959 model, the variation of the molecular-scale temperature is defined as a series of connected segments that are linear in geopotential height from the ground up to 700 kilometers. The general form of each linear segment is:

$$T_M = T_{M,b} + L'_M (H - H_b) \tag{2-11}$$

where $T_{M,b}$ = molecular-scale temperature at the geopotential altitude H_b

L'_M = temperature gradient with respect to H

2.1.1.2 The U.S. Standard Atmosphere 1962

The USSA 1962 model, on the other hand, uses Equation (2-11) only up to a height of 90 kilometers. Above 90 kilometers, T_M is expressed in geometric height Z rather than H. Thus, for Z greater than 90 kilometers,

$$T_M = T_{M,b} + L_M (Z - Z_b) \qquad (2\text{-}12)$$

where L_M denotes the temperature gradient with respect to geometric height Z.

2.1.1.3 The U.S. Standard Atmosphere 1976

The structure of the USSA 1976 model is somewhat more involved. The temperature-altitude profile of USSA 1976 was defined as follows:

1. From Z = 0 to Z = 86 kilometers, T_M is expressed as a series of connected segments linear in H.

2. From Z = 86 kilometers to Z = 1000 kilometers, the kinetic temperature T and the geometric height Z are used to define the temperature-altitude profile.

   a. From Z = 86 kilometers to Z = 91 kilometers, T is constant at 186.8673° K.

   b. From Z = 91 kilometers to Z = 110 kilometers, T(Z) is fitted to an ellipse.

   c. From Z = 110 kilometers to Z = 120 kilometers, T(Z) is linear in Z with a positive gradient.

d. From Z = 120 kilometers to Z = 1000 kilometers, T(Z) is an exponential function.

These first three models (ARDC 1959, USSA 1962, and USSA 1976) represent the year-round average atmosphere in the mid-latitude region over North America.

2.1.1.4 Cospar International Reference Atmosphere 1965

In CIRA 1965 (Reference 4), an attempt was made to develop:

1. A set of atmospheres for the region from 30 kilometers to 80 kilometers for various latitudes and times of the year
2. A set of atmospheres for the region from 120 kilometers to 800 kilometers for various solar fluxes and times of day
3. A Mean Reference Atmosphere for the altitude range from 30 kilometers to 300 kilometers

The Mean Reference Atmosphere was defined as follows:

1. Between 30 kilometers and 80 kilometers, the model represents the mean conditions throughout the year for latitudes near 30 degrees north.
2. Between 120 kilometers and 300 kilometers, the model represents mean conditions over a 24-hour period for a 10.7-centimeter wavelength solar flux, $F_{10.7}$, of 150×10^{-22} w/m^2/Hz.
3. Between 80 kilometers and 120 kilometers, a model was developed that provides a smooth connection between the two parts of the mean atmosphere.

Data published by the U. S. Meteorological Rocket Network and further data from grenade firings were used in preparing the mean and monthly reference atmospheres for CIRA 1965. Most of these data were collected during daytime and at latitudes near 30 degrees north. This model gives not only temperatures, pressures, and densities, but also winds. Furthermore, the latitudinal variations of various atmospheric properties are also included in the model. The tabulations of the models are at intervals of 5 kilometers in height, 10 degrees in latitude, and 1 month in time. In determining the variation of temperature with latitude, use was made of the wind model in conjunction with the thermal wind equation, especially when insufficient temperature data was available.

2.1.1.5 Cospar International Reference Atmosphere 1972

The CIRA 1972 model (Reference 5) follows essentially the same formulation as CIRA 1965. A few notable differences are the following:

1. The lower part of the atmosphere covers the region from 25 kilometers to 110 kilometers.
2. With more data available, the temperature model of CIRA 1972 was obtained without using the thermal wind equation.
3. Additional data were collected and analyzed for the diurnal and semidiurnal variations associated with atmospheric phenomena.

The model temperatures of CIRA 1972 were determined on the basis of observed temperatures from the relationship

$$T_{new}(\theta) = T_{in}(\theta) + a + b\theta + c\theta^2$$

where θ is the latitude in the range 0 degrees to 90 degrees and a, b, and c were obtained using the method of least squares. This procedure was repeated with T_{new} as the next T_{in} until convergence was obtained. Five-point smoothing of T_{new} in height, latitude, and season was then carried out until a smooth model was obtained.

The pressure p and the density ρ were calculated from the temperature T and the 30-kilometer pressure p_0:

$$p = p_o \exp\left[-\int_{Z_o}^{Z} \frac{Mg}{R^* T}\, dZ\right] \qquad (2\text{-}13)$$

$$\rho = pM/R^* T \qquad (2\text{-}14)$$

2.1.1.6 <u>The GISS 1974 Model</u>

The GISS 1974 model (Reference 6) is a global atmospheric circulation model developed at the Goddard Institute for Space Studies (GISS). This model is a nine-level primitive-equation model: the fundamental equations are the equation of motion, the equation of continuity, the equation of state, the first law of thermodynamics, the hydrostatic equation, and a conservation equation for water vapor. These equations are numerically integrated with appropriate sets of initial and boundary conditions. The lower boundary is the Earth's surface and the upper boundary lies at an altitude of about 30 kilometers, which is determined by the upper boundary pressure of 10 millibars. At the lower boundary, the model includes a realistic distribution of continents, oceans, and topography. The model also calculates cloud and water vapor fields and uses them in the calculations of energy transfer by solar and terrestial radiation.

2.1.1.7 ERA Model

The ERA 1975 model (Reference 7) is a mean reference atmosphere based on temperature observations made at Edwards Air Force Base, California, between the years 1953 and 1967 and on previously modeled temperatures, pressures, and densities for Vandenberg Air Force Base, California. The model extends from the surface to an altitude of 700 kilometers. Above 81.75 kilometers, it is identical to the USSA 1962 atmosphere model. Below 81.75 kilometers, the temperature profile was divided into six altitude segments, and a fifth-order polynomial was fitted to each segment. Pressures and densities were derived from the temperature profile below 3.25 kilometers and were taken directly from the Vandenberg model between 3.25 and 81.75 kilometers. These pressure and density profiles were also broken into six segments, and fifth-order polynomials were fitted to the logarithms of the quantities in each segment. The values of the polynomial coefficients, along with a set of profiles calculated from them, is given in Reference 7.

2.1.2 RECOMMENDED MODEL FOR THE LOWER ATMOSPHERE

The Aerodynamic Coefficient Measurement Experiment (ACME) (Reference 8) requires the instantaneous values of atmospheric mass density and wind velocities throughout the Shuttle altitude range during reentry. Among the lower atmospheric models studied, the CIRA 1972 model best meets these requirements. The lower atmospheric part of the CIRA 1972 model gives tabulated atmospheric parameters, i.e., temperature, pressure, density, and wind velocities at intervals of 5 kilometers in height, 10 degrees in latitude, and 1 month in time. Furthermore, the meteorological data used in CIRA 1972 has a high concentration near a latitude of 30 degrees north, which is in the neighborhood of the Shuttle reentry path.

The lowermost 25 kilometers of the atmosphere are not covered by the CIRA 1972 model. For this region, the ERA 1975 model, which was designed with the Shuttle reentry in mind, is recommended. Though no monthly variation is included in this model, a summary of the data[1] from which the model was constructed is available. These data, in monthly form, should allow the amplitude and phase of the yearly variation to be easily determined.

The combination of CIRA 1972 and ERA 1975 will provide a general default lower atmospheric model for latitude 30 degrees north during the major portion of the Shuttle reentry and a more specific default model during the final descent phase into Edwards Air Force Base. The two models merge well at 25 kilometers; for example, the difference between the ERA temperature and the average of the twelve CIRA temperatures at that height is only 0.21° K.

The CIRA 1972 model can easily be replaced by a newer CIRA model when it becomes available (Reference 9).

---

[1] Private communication from J. M. Price of the NASA Langley Research Center.

The diurnal and semidiurnal effects can be incorporated in the following approximate manner. Let f(Z,t) be an atmospheric parameter that is a function of altitude and local solar time, where f(Z,t) is given approximately by (References 5 and 10):

$$f(Z,t) = A_0(Z) + A_1(Z)\cos\frac{\pi}{12}[t - t_1(Z)] + A_2(Z)\cos\frac{\pi}{6}[t - t_2(Z)] \tag{2-15}$$

where

$A_0(Z)$ = diurnal average of f(Z,t)

$A_1(Z)$ = diurnal amplitude at Z

$A_2(Z)$ = semidiurnal amplitude at Z

$t_1(Z)$ = time of the maximum diurnal effect at Z

$t_2(Z)$ = time of the maximum semidiurnal effect at Z

The function f(Z,t) can be written in the following form:

$$f(Z,t) = A_0(Z)\cdot S(Z,t) \tag{2-16}$$

where

$$S(Z,t) = 1 + R_1(Z)\cos\frac{\pi}{12}[t - t_1(Z)] + R_2(Z)\cos\frac{\pi}{6}[t - t_2(Z)]$$

$$R_1(Z) = A_1(Z)/A_0(Z)$$

$$R_2(Z) = A_2(Z)/A_0(Z) \tag{2-17}$$

$A_0(Z)$ can be considered as altitude profiles of respective atmospheric parameters tabulated in CIRA 1972. However, at altitudes below 50 kilometers, the CIRA temperature, pressure, and density are biased towards local noon, and a convenient form of f(z,t) for this case is

$$f(Z,t) = A_{12}(Z) \cdot S(Z,t) / S_{12}(Z) \tag{2-18}$$

where

$$\begin{aligned} S_{12}(Z) &= S(Z,12) \\ &= 1 - R_1(Z)\cos\left(\frac{\pi}{12} t_1(Z)\right) + R_2(Z)\cos\left(\frac{\pi}{6} t_2(Z)\right) \end{aligned} \tag{2-19}$$

Thus, below 50 kilometers, tabulated CIRA 1972 atmospheric parameters can be used in place of $A_{12}(Z)$ in Equation (2-18). In the region below 25 kilometers, diurnal and semidiurnal variations in all parameters are quite small, being generally less than 1 percent of the average value of the parameters except in the lowest kilometer or two of the atmosphere. Thus, it will probably be unnecessary to include diurnal and semidiurnal effects in the bottom segment of the model atmosphere. It will also be relatively easy to include a limited degree of latitude dependence in the lower atmospheric model. This can be accomplished by tabulating sets of latitude gradients for the various parameters at certain altitudes for various times of the year. These gradients can be determined from the 1972 CIRA profiles for altitudes above 25 kilometers and from the ARDC Handbook of Geophysics (Reference 11) for altitudes below 25 kilometers. Clearly, this method allows for accurate calculation of latitude dependence only within a relatively narrow region (e.g., ±10 degrees) centered on 30 degrees north latitude.

2.2 UPPER ATMOSPHERE MODELS

The upper atmosphere starts at altitudes near 100 kilometers and covers the entire thermosphere, which is characterized as a region of rising temperature and diffusive equilibrium. As shown in Figure 2-1, the neutral gas temperature has a profile that increases from a minimum of about 180°K near an altitude of 90 kilometers to a constant value above 300 kilometers that is called the exospheric temperature. Above 300 kilometers, the air density is low and molecular thermal conduction is rapid enough to eliminate any vertical temperature gradient, keeping the neutral gas temperature constant with altitude. The global mean neutral gas exospheric temperature increases with the solar extreme ultraviolet radiation and ranges from several hundred degrees to a few thousand degrees. The atmosphere below 90 kilometers is almost entirely in the molecular state and consists of approximately 78 percent molecular nitrogen, 21 percent molecular oxygen, and 1 percent other minor gas constituents (Reference 3). Above 90 kilometers, in the thermosphere, intense solar ultraviolet radiation can break the molecular bonds, creating atomic species. The photo-dissociation of molecular oxygen into atomic oxygen is particularly effective in the thermosphere. This changes the compositional structure of the atmosphere from a molecular mixture in the lower thermosphere to a mixture rich in atomic oxygen in the upper thermosphere.

There are several types of variation recognized in the thermosphere. They can be classified as follows (References 12 and 13):

1. Variations with solar activity
2. Diurnal variation
3. Variations with geomagnetic activity
4. Semiannual variation
5. Seasonal-latitudinal variations
6. Rapid density fluctuations, probably connected with gravity waves.

Currently available upper atmosphere models have attempted to take into consideration as many of these variations as possible. Among these available models, the following models were chosen for evaluation:

- Harris-Priester 1962 model
- Jacchia-Roberts 1971 model
- Jacchia 1977 model
- MSIS 1977 model
- Russian models

In these models, variations of atmospheric parameters with solar activity were formulated in terms of the solar 10.7-centimeter radio flux, which is known to be closely related to the solar extreme ultraviolet (EUV) radiation, one of the main heat sources for the upper atmosphere. The solar 10.7-centimeter radio flux can be measured from the ground, while the solar EUV radiation cannot be measured at ground level because of strong absorption in the upper atmosphere. This flux, denoted as F10.7, gives a measure of the 10.7-centimeter flux in units of 10^{-22} w/m^2/Hz. $F_{10.7}$ values range from about 70 at minimum solar activity to about 250 at maximum solar activity.

2.2.1 EVALUATION OF AVAILABLE MODELS

2.2.1.1 Harris-Priester 1962 Model

In 1962, Harris and Priester (Reference 10) developed a time-dependent model of the upper atmosphere using the energy equation and the barometric equation. This model is one-dimensional in the sense that the only space coordinate considered is the height Z. The second independent parameter in the model is the local solar time, which is equivalent to the longitude. Latitudinal dependence is completely disregarded. The procedure is based upon a perturbation approach suggested by Eckart (Reference 14) in which the temperature profile at the time $t+\Delta t$ is obtained from the energy-temperature equation using the known temperature profile, atmospheric density, and energy input at the time t. Harris and Priester used two energy sources, one due to the extreme ultraviolet radiation of the Sun and the other to account for any other possible sources of energy.

The second energy source was assumed to have approximately the same daily integrated intensity and the same height dependence as the EUV source. The time of the diurnal maximum of the second source was chosen such that the calculated temperature profiles and density variations were in agreement with those obtained from satellite drag measurements. There are two variations of this original Harris-Priester approach. One is the Modified Harris-Priester Model used in the Goddard Trajectory Determination System (GTDS) (Reference 15) and the other is the Asymmetric Modified Harris-Priester Model introduced by Dowd and Tapley (Reference 16). The Modified Harris-Priester Model uses tabulated daytime maximum and nighttime minimum density values at various altitudes and $F_{10.7}$ values. These tables were constructed from a similar, but more extensive, tabulation given in CIRA 1965 (Reference 4). Using the maximum and minimum densities, $\rho_{max}(h)$ and $\rho_{min}(h)$, at an altitude h, the density at h is given by

$$\rho(h) = \rho_{min}(h) + [\rho_{max}(h) - \rho_{min}(h)] \cos^n\left(\frac{\Psi}{2}\right) \qquad (2\text{-}20)$$

$$(2 \leq n \leq 8)$$

where Ψ is the angle between the position vector of the point where the density is desired and the apex of the diurnal bulge. This procedure yields a density distribution that is symmetric with respect to the apex of the diurnal bulge. However, it is known (Reference 17) that the observed diurnal variation is not symmetric. To incorporate this asymmetric diurnal variation in the Harris-Priester model, Dowd and Tapley (Reference 16) proposed the Asymmetric Modified Harris-Priester Model. In this model, the asymmetric diurnal formulation developed for temperature profiles by Jacchia (Reference 13) was used to compute a diurnally asymmetric density distribution. The density at h is given by

$$\rho(h) = \rho_N(h) + [\rho_D(h) - \rho_N(h)] \cos^n\left(\frac{\tau}{2}\right) \qquad (2\text{-}21)$$

where

$$
\begin{aligned}
\rho_N(h) &= \rho_{min}(h)\left[1 + Q \sin^m \zeta\right] \\
\rho_D(h) &= \rho_{min}(h)\left[1 + Q \cos^m \eta\right] \\
Q &= \left[\rho_{max}(h) - \rho_{min}(h)\right] / \rho_{min}(h) \\
\zeta &= \tfrac{1}{2}\left|\theta + \delta\right| \\
\eta &= \tfrac{1}{2}\left|\theta - \delta\right| \\
\tau &= H + \beta + \lambda(H + \gamma) \qquad (-\pi < \tau < \pi)
\end{aligned}
\tag{2-22}
$$

In these equations, H is the local solar time, θ is the latitude of the subsatellite point, and δ is the solar declination. The values of the parameters appearing in Equations (2-22), taken from Jacchia's temperature equation (Reference 13), are:

$$
\begin{aligned}
m &= 2.2 \\
\beta &= -37^\circ \\
\lambda &= 6^\circ \\
\gamma &= 43^\circ
\end{aligned}
$$

The two versions of the modified Harris-Priester model described above explicitly include in the computation of the atmospheric density only the first two variations listed in Section 2.2, namely, the effects of the solar 10.7-centimeter flux level and the diurnal variation.

2.2.1.2 Jacchia-Roberts Model

The Jacchia 1971 Model (Reference 12) describes an upper atmosphere above 90 kilometers. This model is based upon a family of vertical temperature profiles that were constructed from observed data. The computation of the atmospheric density involves solving a pair of differential equations using an appropriate temperature profile. The two equations are the diffusion equation for the number density of individual species above an altitude of 100 kilometers and the barometric equation for the mean density of the entire constituents of the atmosphere between 90 kilometers and 100 kilometers. The Jacchia-Roberts model implemented in GTDS (Reference 15) uses analytical solutions to these differential equations given by Roberts (Reference 18). The Jacchia-Roberts model includes the effects associated with the solar 10.7-centimeter flux, the diurnal variation, and geomagnetic activity in the computation of temperature profiles. The semiannual and seasonal-latitudinal variations were incorporated into the final density calculation.

Each temperature profile is labelled by the so-called exospheric temperature, T_∞, which sets the upper boundary value for the temperature. T_∞ is computed in three steps in the Jacchia-Roberts model. First, from the solar 10.7-centimeter flux level, the nighttime minimum exospheric temperature, T_C, is obtained

$$T_C = 379^\circ + 3^\circ.24 \bar{F}_{10.7} + 1^\circ.3 (F_{10.7} - \bar{F}_{10.7}) \qquad (2\text{-}23)$$

The second step involves computing T_{DNL}, the exospheric temperature which includes the diurnal variation, from T_C:

$$T_{DNL} = T_N + (T_D - T_N) \cos^3 \frac{\tau}{2} \qquad (2\text{-}24)$$

where

$$T_D = T_c \left(1 + 0.3 \cos^m \eta \right)$$
$$T_N = T_c \left(1 + 0.3 \sin^m \zeta \right) \qquad (2\text{-}25)$$

Various parameters appearing in these equations have already been defined in Equation (2-22). Finally, in the third step, the contribution to T_∞ from the geomagnetic activity effect is computed, i.e.,

$$(\Delta T_\infty)_{GMG} = 28^\circ K_p + 0^\circ\!.03\, e^{K_p} \quad (Z > 200\text{ Km})$$
$$= 14^\circ K_p + 0^\circ\!.02\, e^{K_p} \quad (Z < 200\text{ Km}) \qquad (2\text{-}26)$$

where K_p is the 3-hour geomagnetic planetary index. An average time lag of 6.7 hours was used for the time lag associated with the atmospheric variation resulting from the geomagnetic disturbance.

The total exospheric temperature is given by

$$T_\infty = T_{DNL} + (\Delta T_\infty)_{GMG} \qquad (2\text{-}27)$$

The value of T_∞ uniquely determines the temperature profile to be used in the computation of the density, which will be further corrected for the semiannual and seasonal-latitudinal variations. See Reference 13 for details of these corrections.

2.2.1.3 The Jacchia 1977 Model

The general structure of Jacchia's 1977 model (Reference 19) is identical to that of his 1971 model. Temperature profiles obtained using the 10.7-centimeter solar flux, the diurnal variation, and the geomagnetic activity effect are used to compute the atmospheric density from the diffusive equations above 100 kilometers and the barometric equation is used below 100 kilometers. The differences between the two models are primarily in the details of the calculation of the temperature profiles.

In Jacchia 1977, the arithmetic mean of the nighttime minimum and the daytime maximum exospheric temperature, $T_{\frac{1}{2}}$, is related to the 10.7-centimeter solar flux index $F_{10.7}$ as follows:

$$T_{\frac{1}{2}} = 5.48\,\bar{F}_{10.7}^{0.8} + 101.8\,F_{10.7}^{0.4} \tag{2-28}$$

where $\bar{F}_{10.7}$ is a weighted mean of $F_{10.7}$, the weight being a Gaussian function of time centered on the current time.

The diurnal variation of temperature was formulated for each constituent of the atmosphere in terms of $T_{\frac{1}{2}}$, the declination of the Sun, and the hour angle of the Sun. The diurnal temperature curve has a somewhat more complicated shape than that of the 1971 model. The total density maximum and minimum occur at 16.8 hours and 5.4 hours local solar time, respectively. These values are to be compared with 14 hours and 3 hours local solar time in the 1971 model.

Also, a much more sophisticated approach is used in computing the geomagnetic activity effect in the 1977 model. The latitude-dependent time lag is empirically derived with the minimum time lag of 2.4 hours at the geomagnetic poles and the maximum time lag of 7.2 hours at the equator. Furthermore, the exospheric temperature increase due to the geomagnetic activity effect is assumed to accompany a change in the height of the homopause, which is the point where the atmosphere ceases to be a homogeneous mixture of its various components. The change in the height of the homosphere brings about a change in density due to the equatorial wave, which is the density pileup in the equatorial regions as a consequence of convection toward the equator. The semiannual and seasonal-latitudinal variations have been taken into account in a way similar to that in the 1971 model.

2.2.1.4 The MSIS 1977 Model

The MSIS model (Reference 20) is a purely empirical model based upon a large amount of mass spectrometer and incoherent scatter measurement data. These data were provided by mass spectrometers on five satellites (Orbiting Geophysical Observatory-6 (OGO-6), San Marco-3, Aeronomy Satellite-1 (AEROS-1), Atmosphere Explorer-2 (AE-2), and AE-3) and four incoherent-scatter ground stations (Arecibo, Jicamarca, Millstone, and St. Santin). The exospheric temperature and other quantities were represented by expansions in terms of spherical harmonics. The lower boundary of the MSIS model is at an altitude of 120 kilometers.

The model coefficients are determined in a series of steps that consider independently (1) 120-kilometer temperatures, (2) 120-kilometer densities, (3) exospheric temperatures and temperature gradient parameters under quiet magnetic conditions, and (4) high magnetic activity.

The MSIS model includes the 10.7-centimeter solar flux effect, the geomagnetic activity effect, the diurnal and semidiurnal variations, the annual and semiannual variations, and seasonal-latitudinal variations.

2.2.1.5 The Russian Model

The Russian atmospheric model is derived from the U.S.S.R. Cosmos satellite deceleration results collected over the period from 1964 through 1970 (Reference 21). This model determines the atmospheric density by fitting density observations over the range of altitudes and temperatures encountered by the Cosmos satellites. Use of this model is restricted because the coefficients were empirically determined over a limited altitude region and during only a portion of the 11-year solar cycle. The data were extended by using Jacchia's 1970 model (Reference 22). See References 16 and 21 for further details.

2.2.2 RECOMMENDED MODEL FOR THE UPPER ATMOSPHERE

The Jacchia-Roberts model, with several modifications developed in the Jacchia 1977 model, is recommended as the upper atmosphere model for LAIRS. The modifications involve using new parameters for the diurnal variation and the latitude-dependent time lag for the geomagnetic activity effect. With these modifications, the Jacchia-Roberts model explicitly includes most of the important atmospheric variations, and is not as complicated as the Jacchia 1977 or the MSIS model. The Jacchia-Roberts model can also be easily readjusted by updating only a few parameters which determine the basic structure of the temperature profiles.

2.3 WIND MODELS

Winds are a direct result of pressure and temperature differences in the atmosphere and can be mathematically derived from a given pressure-temperature distribution. Alternatively, winds can be modeled by assuming a set of empirical wind profiles as a default model and using observed wind velocities to adjust this model. The following sections elaborate on these two possibilities, drawing primarily on References 23 and 24 for the discussion of the analytic approach, and on the CIRA 1972 wind profiles (Reference 5) for the empirical model discussion. Figure 2-2 shows two typical wind profiles.

2.3.1 EVALUATION OF AVAILABLE MODELS

2.3.1.1 Analytic Model

The acceleration of an air parcel relative to the Earth can be expressed in terms of the pressure gradient and the acceleration due to the Coriolis force, frictional forces, and gravity. For frictionless flow, and neglecting the small terms introduced by the curvature of the Earth, the acceleration equations are as follows:

$$\frac{du}{dt} = 2\omega v \sin\theta - \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad (2\text{-}29)$$

$$\frac{dv}{dt} = -2\omega u \sin\theta - \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad (2\text{-}30)$$

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad (2\text{-}31)$$

where x, y, and z represent the eastward, northward, and upward directions, respectively, and u, v, and w are the velocities corresponding to these directions. The angular velocity of the Earth is denoted by ω , θ is the latitude, ρ is the density, and p is the pressure. Because vertical wind velocities are much smaller than horizontal velocities, the Coriolis term has been deleted from Equation (2-31).

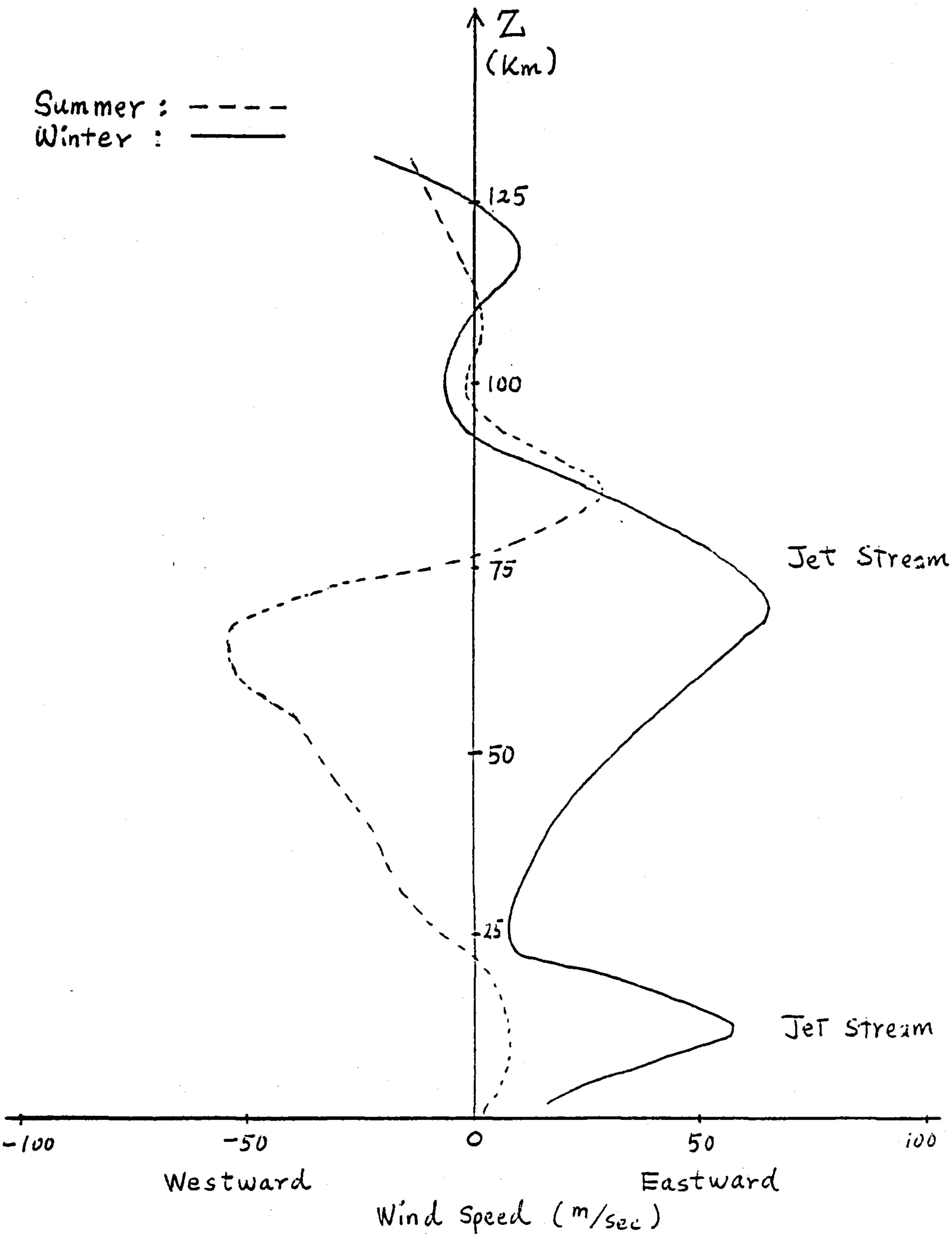

Figure 2-2. Typical Summer and Winter Wind Profiles (30 Degrees North Latitude)

In the Earth's atmosphere, the accelerations on the left sides of Equations (2-29) through (2-31) are generally an order of magnitude smaller than the terms on the right. The geostrophic approximation consists of setting these accelerations to zero, so that the pressure gradient is balanced by the Coriolis force. This yields

$$v = \frac{1}{2\rho\omega\sin\theta}\frac{\partial p}{\partial x} \tag{2-32}$$

$$u = \frac{-1}{2\rho\omega\sin\theta}\frac{\partial p}{\partial y} \tag{2-33}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g \tag{2-34}$$

Equation (2-34) is the equation of hydrostatic equilibrium and Equations (2-32) and (2-33) are its analogs in the horizontal directions, i.e., the <u>geostrophic wind</u> equations.

In the presence of a high or low pressure system, Equations (2-29) and (2-30) must be modified to include the centrifugal force term arising from air flow about the high or low. If R is the radius of curvature of the flow, the geostrophic approximation gives rise to the <u>gradient wind</u>, i.e.,

$$V = R\omega\sin\theta - \sqrt{(R\omega\sin\theta)^2 - \frac{R}{\rho}\frac{\partial p}{\partial n}} \tag{2-35}$$

for flow about a high pressure system, and

$$V = \sqrt{(R\omega \sin\theta)^2 + \frac{R}{\rho}\frac{\partial p}{\partial n}} - R\omega \sin\theta \qquad (2\text{-}36)$$

for flow about a low pressure system. In these equations, V denotes the magnitude of the horizontal wind velocity and $(\partial p/\partial n)$ denotes the radial gradient of the pressure. There is a limit to the velocity of flow about a high pressure system, since the term under the radical must be positive, but there is no corresponding limit to flow velocities about a low pressure system. The latter situation holds in the case of hurricanes.

The geostrophic approximation can be used to derive (Reference 23) the vertical wind shear produced by nonuniform horizontal heating:

$$\mathcal{U}(Z_2) - \mathcal{U}(Z_1) = \frac{R^*}{\overline{M}\,(2\omega \sin\theta)} \left(\frac{\partial T}{\partial y}\right)_p \ln \frac{P_1}{P_2} \qquad (2\text{-}37)$$

This is one form of the thermal wind equation. There is a similar equation for meridional flow (v). Here R^* is the universal gas constant and $\overline{M}$ is the mean molecular weight. Thus, given a horizontal temperature (T) distribution and the pressures p_1 and p_2 at altitudes Z_1 and Z_2 $(Z_2 > Z_1)$, one can determine the difference in wind velocity between those two heights. For most of the atmosphere, the combination of the geostrophic wind ($\mathcal{U}_g$) and the thermal wind ($\mathcal{U}_T$) has been found to be an adequate description of wind structure, the thermal wind giving the increment in the geostrophic wind with altitude, i.e.,

$$\mathcal{U}_g(Z_2) = \mathcal{U}_g(Z_1) + \mathcal{U}_T(Z_1, Z_2) \qquad (2\text{-}38)$$

where u_T is the quantity given by Equation (2-37) and u_g is given by Equation (2-33).

The geostrophic approximation, which gives rise to all of the above wind equations, is valid above the lowermost 1 or 2 kilometers of the atmosphere (the planetary boundary layer). There friction is important and topographical features make modeling of winds extremely difficult in general. Also, in the region between 80 and 120 kilometers altitude, ionospheric electrojet activity produces sporadic winds which cannot be treated by the wind equations (Reference 25). Thus, the analytic model is of use only between the altitudes of (approximately) 2 and 80 kilometers. When the radius of curvature of the flow is known from sources such as satellite weather maps, the gradient wind equation can also be used.

2.3.1.2 Empirical Model

Vertical profiles of the zonal wind (u) are given for various latitudes and for each month of the year by CIRA (1972). These profiles cover the altitude range of 25-100 kilometers. The meridional wind (v), which is much smaller than the zonal wind at these altitudes, is not tabulated but may be estimated from accompanying diagrams. These profiles show significant monthly variations, mainly because of the strong jet stream around 60 kilometers which reverses direction seasonally. This seasonal change of profile shape, together with the fact that above 80 kilometers the monthly profiles show little resemblance to each other, makes a polynomial fitting scheme impractical. Interpolation between data points stored on permanent files would have to serve as a default model. No model adjustment would be possible; the observed wind profiles would merely replace the default profiles before the interpolation began.

The situation is much the same below 25 kilometers, except that there the source of the default data is information received directly from LaRC. As with the models for the other atmospheric parameters covered in Section 2.1, diurnal, semidiurnal, and latitudinal effects can be introduced into the wind model. The latitude variation can be derived from tabulated gradients of the wind components (based on information in References 5 and 24; the diurnal and semidiurnal variations can be modeled by Equation (2-15). Amplitudes of the diurnal and semidiurnal east-west wind variations are charted in CIRA 1972 up to an altitude of 80 kilometers. Above that height, diurnal and semidiurnal wind variations have been studied by Fellous et al. (Reference 26), who provide a mathematical scheme for approximating the east-west wind amplitude. It is known that the amplitudes and phases of the diurnal and semidiurnal wind variations change with season and may change from day to day, but these changes have not been well studied.

2.3.2 RECOMMENDATION OF A WIND MODEL

As pointed out in Section 2.3.1.1, the analytic model of wind structure is limited to regions below an altitude of 80 kilometers. The primary advantage of the analytic model is that it requires no input other than temperature, pressure, and density distributions at a given time and location. If longitudinal, latitudinal, diurnal, and seasonal effects have been adequately modeled in the state variables, they will automatically be included in the calculated winds. However, enough measurement profiles to provide a good estimation of the latitudinal and longitudinal (or hour angle) gradients of temperature and pressure are required by this model. It will not be adequate to use default values of these gradients together with measured profiles to obtain the wind components, as these components are linearly proportional to the gradients: i.e., a 100-percent error in a pressure gradient would produce a 100-percent error in calculated wind speed, although it would produce only a 1-percent or 2-percent error when used to extrapolate pressure a few degrees (most such gradients are quite small). In addition, sporadic gusts and turbulence cannot be modeled by the wind equations.

The empirical model has important drawbacks as well. One is that no actual modeling of vertical wind structure is possible--only interpolation between default or measured data points. Another drawback is the incomplete knowledge of diurnal and semidiurnal wind variatons. These must be included not only because the Shuttle covers several hours of local time in a few minutes, but also because there may be a time lag between the measurement of the wind profiles and the reentry of the Shuttle (because daily variations are quite small below an altitude of 30 kilometers and because the Shuttle spends little time and covers little horizontal distance in this region, it is recommended that diurnal and semidiurnal variations not be modeled below 30 kilometers).

In summary, either the analytic or the empirical model can be used to model the wind. If there will not be enough meteorological data available to allow accurate determination of temperature and pressure gradients, the analytic model should be avoided. Therefore, it is recommended that the empirical model serve as the primary method of wind determination, since it is not yet certain how many meteorological profiles will be available for a typical Shuttle reentry. However, certain routines should be provided so that the analytic model can be used in the event that accurate determination of pressure and temperature gradients becomes possible.

SECTION 3 - FITTING PROCEDURES

Meteorological data obtained from the National Oceanic and Atmospheric Administration (NOAA) contain vertical profiles of temperature, pressure, density, and wind at a specified longitude, latitude, and local solar time. This section presents a description of a method for finding adjusted model altitude profiles, adjusted diurnal and semidiurnal variations, and the adjusted latitude dependence of the atmospheric model from these meteorological data. Section 3.1 contains a discussion of the diurnal and latitudinal variations and Section 3.2 deals with the fitting of altitude profiles. Section 3.3 dicsusses wind profiles and Section 3.4 contains some discussion of accuracy estimation for the fitting procedures.

3.1 DIURNAL, SEMIDIURNAL, AND LATITUDINAL VARIATIONS

The observed vertical profiles will be labeled by the local solar time, t, and the latitude, θ. Local solar time effects, i.e., the diurnal and semidiurnal variations, and the latitude dependence of the atmosphere will be explicitly considered insofar as the distribution of observation data allows. New diurnal and semidiurnal amplitude and phase relationships can be obtained from a set of altitude profiles, all having the same reference latitude, θ_R. These profiles can be obtained by latitude translation (to latitude θ_R) using the default (CIRA) latitude dependence. These profiles must have a reasonably good distribution in local solar time so that new diurnal and semidiurnal variations can be calculated. Having found a new diurnal and semidiurnal variation, a new latitude dependence can be determined from a similar set of vertical profiles, all having the same reference local solar time, t_R, with a finite spread in latitude. This set of vertical profiles can be constructed by local solar time translation using the new diurnal and semidiurnal variations. Finally, a large composite reference altitude profile at (θ_R, t_R) can be constructed from the original set of observed vertical profiles using the newly obtained diurnal and latitudinal variations.

Let $\mathcal{P}^i(\theta_i, t_i)$ denote the ith vertical profile in the original set of observed vertical profiles, and let $\mathcal{D}(t_i, t_R)$ and $L(\theta_i, \theta_R)$ denote the newly computed diurnal and latitudinal translations, respectively. First $\mathcal{P}^i(\theta_i, t_i)$ is translated from (θ_i, t_i) to the reference point (θ_R, t_R). This translated profile is denoted as $\mathcal{P}^i(\theta_R, t_R)$:

$$\mathcal{P}^i(\theta_R, t_R) = \mathcal{D}(t_i, t_R) L(\theta_i, \theta_R) \mathcal{P}^i(\theta_i, t_i) \tag{3-1}$$

Then the reference profile, $\mathcal{P}(\theta_R, t_R)$, is constructed as

$$\mathcal{P}(\theta_R, t_R) = \bigcup_i \mathcal{P}^i(\theta_R, t_R) \tag{3-2}$$

This reference profile is a composite set of many profiles merged into one. $\mathcal{P}(\theta_R, t_R)$ will be used to fit a model altitude profile at (θ_R, t_R) .

3.2 FITTING PROCEDURES FOR VERTICAL PROFILES

Reference vertical profiles constructed in Section 3.1 for temperature, pressure, and density will be used to derive respective model altitude profiles. Temperatures will be fitted to a set of polynomials of Z for the lower atmosphere and to the Jacchia-Roberts temperature profile for the upper atmosphere. In the case of pressure and density, $\ln(P/p_0)$ and $\ln(\rho/\rho_0)$ will similarly be fitted to a set of polynomials and to the Jacchia-Roberts model. The quantities p and ρ denote the pressure and density, respectively, and the subscripted quantities represent values at a reference altitude.

3.2.1 TEMPERATURE PROFILES

The entire altitude range is divided into four regions as shown in Figure 3-1. At the boundary between two consecutive regions, the temperature is required to be continuous. The Jacchia-Roberts temperature profile will be used for the uppermost region which starts at an altitude (Z_1^B) near 120 kilometers. When there are enough observation data available to cover up to and beyond 125 kilometers, Z_1^B will be taken as 125 kilometers. Then the Jacchia-Roberts temperature profile to be used for the uppermost region ($Z > 125$ kilometers) takes the following form:

$$T_1(Z) = T_\infty - (T_\infty - T_1^B)\, e^{-E(Z)} \tag{3-3}$$

$$E(Z) = G_1^B \, \frac{Z - Z_1^B}{T_\infty - T_1^B} \cdot \frac{R_a + Z_1^B}{R_a + Z}$$

where

T_∞ = exospheric temperature

T_1^B = temperature at Z_1^B

G_1^B = upper temperature gradient at Z_1^B

R_a = constant = 6356.766 kilometers

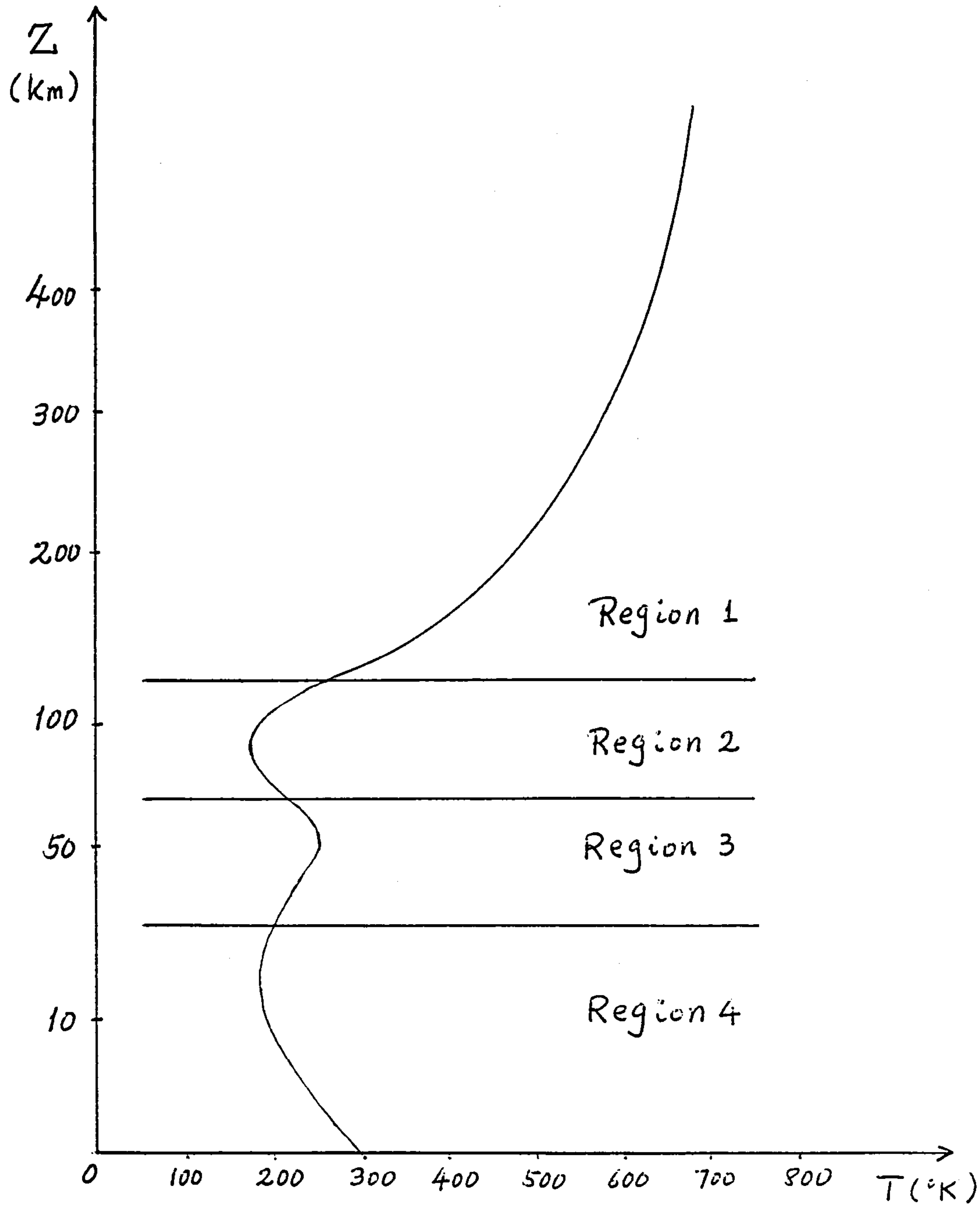

Figure 3-1. Temperature-Altitude Regions

For altitudes below 125 kilometers, the following sets of polynomials will be used:

$$T_i(Z) = T_{i-1}^B + \sum_{n=1}^{N_i} C_{in}(Z - Z_{i-1}^B)^n , \quad Z_{i-1}^B \geq Z > Z_i^B$$

$$(i = 2, 3, 4) \tag{3-4}$$

where

T_{i-1}^B = temperature at Z_{i-1}^B

N_i = order of the polynomial for region i

Parameters T_i^B $(i=1\sim3)$, G_1^B, C_{in} $(n=1\sim N_i ; i=2,3,4)$ and a part of T_∞ can be readjusted such that $T_i(Z)$ $(i=1\sim4)$ best fit the observed temperature data. When there are not enough data to cover all regions, a subset of the above parameters can be selected to be solved for. Mathematical details of these procedures will be given in Section 4.3.2.

3.2.2 DENSITY AND PRESSURE

Pressures and densities could be obtained from the temperature profile computed in Section 3.2.1 using Equations (2-13) and (2-14). However, the quantities can also be fitted directly if observation data for temperature, density, and pressure are available from independent sources. In this case, the entire altitude range is divided into four regions as in the case of temperature. The Jacchia-Roberts density model will be used for the uppermost region and a set of polynomials for the lower regions. A set of functions $\{F_i(Z)\}$ defined as

$$F_i(Z) = -\ln\left(\rho(Z)/\rho_0\right) \qquad (i = 1 \sim 4) \tag{3-5}$$

will be used in the fitting procedure. The $\rho(Z)$ term denotes a density value at Z and ρ_o denotes a reference density at a reference altitude.

$$F_1(Z) = -\ln\left(\rho_{JR}(Z)/\rho_o\right) \qquad Z \geq Z_1^B$$

$$F_i(Z) = F_{i-1}^B + \sum_{n=1}^{N_i} C_{in}\,(Z - Z_{i-1}^B)^n \qquad (3-6)$$

$$Z_{i-1}^B \geq Z > Z_i^B$$

$$(i = 2, 3, 4)$$

where

$\rho_{JR}(Z) =$ Jacchia-Roberts density

$F_{i-1}^B = F_{i-1}(Z_{i-1}^B)$

Parameters F_i^B (i = 1,2,3), C_{in} ($n=1 \sim N_i$; $i=2 \sim 4$) and the Jacchia-Roberts temperature parameters can be adjusted such that $\{F_i(Z)\}$ best fits the observed altitude profile for the atmospheric density.

A similar approach can be used for pressure. In this case $F_1(Z)$ is defined as follows.

$$F_1(Z) = -\ln\left(P_{JR}(Z)/P_o\right)$$

$$P_{JR}(Z) = R^*T\,\rho_{JR}(Z)/\overline{M}(Z) \;:\; Z \leq 100\text{ Km} \qquad (3-7)$$

$$= R^*T \sum_{\ell} n_\ell / N_A \;:\; Z > 100\text{ Km}$$

In these equations, M(Z) denotes the mean molecular weight, N_{ℓ} the number density of each individual species, and N_A Avogadro's number. The first expression for p_{JR} applies to the region of barometric equilibrium and the second expression applies to the region of diffusive equilibrium.

3.3 WIND

Observed wind data will be processed according to the same procedures described in Section 3.1 for the diurnal, semi-diurnal, and latitudinal variations of temperature, pressure, and density. However, its vertical profile will not be fitted to any model, but rather a simple and straightforward interpolation scheme will be used throughout to find wind velocities at various points along the Shuttle trajectory.

As an option, a theoretical wind profile can be created using the spatial variations of temperatures and pressures (see Section 2.3).

3.4 ACCURACY ESTIMATION

Examples of the NOAA meteorological profiles that are expected to be available after each Shuttle flight have been provided by LaRC.[1] The measurement errors accompanying these profiles show that, in the lowest 25 kilometers of the atmosphere, the uncertainties in temperature, pressure, and density are all less than 2 percent. Between 25 and 75 kilometers, they may reach 10 percent or more. Numerical experiments using this sample meteorological data and the polynomial fitting procedure discussed in Section 3.2 indicate that errors resulting from the polynomial fitting itself can easily be kept within this range. For example, fitting two third-order polynomials (constrained to join and be continuous at an altitude of 25 kilometers) to the sample data between the surface and 65 kilometers results in a standard deviation of 4° K, or about 1.5 percent of the typical temperature in that region. Even better results (1° K - 3° K) are obtained when the smoothed CIRA or ERA profiles are fitted.

[1] Private communication from J. M. Price.

The situation with wind errors is less encouraging. The sample meteorological profiles show that errors of between 10 and 20 percent of the total wind speed are possible below 75 kilometers, and that uncertainties of up to 100 percent may occur above that level. No uncertainties or standard deviations are given for the CIRA profiles. However, mean deviations of observed winds from modeled winds are given for certain locations. These deviations are quite variable, but generally show the same situation as do the meteorological data: below 75 kilometers, the modeled winds are often off by 10 or 20 percent; above 75 kilometers they are sometimes off by as much as 100 percent. These errors must be accepted as the limits of wind modeling. When wind uncertainties are considered, however, it should be recalled that in the altitude region where the largest errors are expected, the Shuttle velocity will be greater than 5 kilometers per second. The wind speeds there are at most 100 meters per second, so even if the winds were 100 percent in error, this error would be no more than 2 percent of the Shuttle velocity.

It is also important to consider errors in the modeling of diurnal and semidiurnal variations. As pointed out previously, below 25 kilometers, these effects are small enough to be ignored, except in the planetary boundary layer. Above 25 kilometers they grow rapidly, primarily because of absorption and re-radiation by the ozone layer. The amplitude of the diurnal temperature tide can reach 10° K (4 percent) around 50 kilometers; the amplitudes of the diurnal and semidiurnal components of pressure and density variations range between 6 percent and 12 percent near 80 kilometers. Wind amplitudes at such heights may reach 10 to 30 meters per second. Thus, in 3 to 6 hours (local time) the atmospheric parameters undergo variations that can exceed measurement error at some altitudes, and should therefore be incorporated into the model. Unfortunately, the amplitudes and phases of these variations change greatly with the seasons, and these changes have been poorly studied. Sources such as CIRA 1972 provide only an incomplete mapping of diurnal and semidiurnal effects. Reliance on the default model of daily variations (as would be necessary when only one or two profiles were available) could conceivably introduce errors of 10 to 12 percent in some parameters above 50 kilometers.

The effect of errors in the latitude gradients may be readily estimated. From the CIRA 1972 profiles it can be seen that these quantities are quite small, with typical temperature gradients at 30 degrees north latitude being only a few tenths of a degree Kelvin per degree latitude. Pressure and density gradients are marginally more significant. Still, it is extremely unlikely that errors in the values of the latitude gradients would produce uncertainties in the model parameters exceeding the uncertainties due to measurement error.

Finally, the consistency of the models studied will be briefly considered. As discussed in Section 2.1, the difference between the average of the twelve 30-degree-north-latitude CIRA temperature profiles and the mean ERA 1975 profile is less than 1° K at 25 kilometers. The differences for pressure and density are greater, but are still less than 4 percent. These are about the same magnitudes as the differences between either of these models and USSA 1962 near 25 kilometers. The Jacchia 1977 model assumes a temperature minimum at 90 kilometers, and takes the USSA 1976 value of 188° K at that point. The CIRA profiles at 30 degrees north average 189° K at 90 kilometers. The difference between the CIRA density and the Jacchia 1977 (USSA 1976) density at 90 kilometers is 3 percent. Thus, all the models considered are consistent. The combination of the ERA 1975, CIRA 1972, and Jacchia-Roberts models has been recommended because it is believed to offer the most comprehensive, flexible, and easily implemented atmospheric modeling scheme.

SECTION 4 - FUNCTIONAL SPECIFICATIONS

This section details the software requirements and specifications for the Langley Atmospheric Information Retrieval System (LAIRS). Mathematical specifications are also discussed, along with input/output requirements.

4.1 SOFTWARE REQUIREMENTS

The LAIRS software must be designed to perform the following functions:

- Respond to user input specifying program options
- Receive an input ENTREE Program trajectory file containing Shuttle position versus time
- Receive input meteorological measurements containing vertical profiles of temperature, pressure, density, horizontal wind speed, and horizontal wind direction from various stations along or near the Shuttle reentry path
- Produce values of the atmospheric parameters (temperature, pressure, density, and horizontal wind components) for points on the Shuttle trajectory, using the input meteorological data as a basis for calculation
- Provide default values of the atmospheric parameters when no or insufficient meteorological observations are available
- Produce output reports and an output user file containing the values of the calculated parameters

The calculation of the atmospheric parameters can take one of three forms: calculation based on the default coefficients derived from the Jacchia-Roberts, CIRA 1972, and ERA 1975 models discussed in Section 2; calculation based on adjusted coefficients determined from the default coefficients and the input meteorological data by the fitting procedure discussed in Section 3; and a simple interpolation of the nearest meteorological profile with no attempt at any sort of modeling. The default coefficients will be stored on permanent files and the adjusted coefficients will be stored on working files. The software must thus be able to create and access the appropriate files in order to perform the necessary calculations.

The software for adjusting the model coefficients will be the most complex part of the system. As discussed in Section 3, least-squares techniques will be the basis of the adjustment procedure. It will be possible, however, to adapt certain ENTREE Program routines to the model-fitting process, thereby lessening the development time required for this section of LAIRS.

The following options will be available to the user:

- Calculate parameters based on the default model, on the adjusted model, or on the interpolation scheme
- Produce an Atmospheric Parameter Output Report (APOR) giving the calculated parameters along the Shuttle trajectory
- Produce a Local Atmospheric Profile (LAP) version of the Atmospheric Parameter Output Report, giving a set of vertical profiles of the calculated parameters for a specified latitude, longitude, and time

- Rebuild the permanent files using input meteorological observations. This option would be useful in the event new CIRA profiles become available, for example.

4.2 INPUT

4.2.1 TRAJECTORY DATA

The LAIRS input trajectory data will be the output trajectory file of LaRC's ENTREE Program, giving Shuttle position as a function of time. The contents of this file that will be utilized by LAIRS are shown in Table 4-1.

4.2.2 OBSERVATION DATA

The meteorological observations required by the model adjustment process will be supplied by NASA on a nine-track magnetic tape after each Shuttle flight. The format will be that of the Meteorological Input Tape described in Reference 27. The information supplied will consist of a set of vertical profiles of temperature, pressure, density, wind speed, wind direction, and the uncertainty in each of these measurements (the dewpoint is also provided on the tape, but will not be used by LAIRS). These profiles will cover the region from 0 kilometers to at least 120 kilometers, and are expected to be provided by several stations along the Shuttle reentry path. Each profile is assumed to have a time tag (GMT) that is within one-half hour of the time the profile was obtained. It will not be necessary for each point in the profile to be tagged. The format of the meteorological data required by LAIRS is shown in Table 4-2.

4.2.3 CONTROL DECKS

LAIRS will be designed to accept as input a limited number of keyword cards giving the specific options selected from

Table 4-1. Variables to Be Read From ENTREE Trajectory File

VARIABLE	TYPE	LENGTH	DESCRIPTION
TIME	REAL	1	Time tag of state vector (GMT)
X	REAL	3	State vector: altitude (meters), latitude (degrees east), longitude (degrees north)
XSTD	REAL	3	Standard deviations of the state vector components

Table 4-2. Format of LAIRS Meteorological Data Tape (1 of 2)[1]

WORD	SYMBOL	DESCRIPTION	UNITS
1	LAT	Latitude	Degrees, + N
2	LON	Longitude	Degrees, + E to 360
3	FLAG	Data flag: = 0, measured data = 1, modeled data = 2, combined measured and modeled data	
4	--	Spare	
5	ALT	Geometric altitude	Feet
6	WS	Horizontal wind speed	Feet/second
7	WD	Direction horizontal wind is coming relative to true north, north being 0 degrees, increasing positively clockwise	Degrees
8	TE	Ambient temperature	Degrees C
9	PR	Ambient pressure	Millibars
10	D	Ambient density	Grams/meter^3
11	DW	Dew point (not used)	Degrees C
12	TEU	Ambient temperature systematic uncertainty	Degrees C
13	PRU	Ambient pressure systematic uncertainty	Millibars
14	DU	Ambient density systematic uncertainty	Grams/meter^3
15	HWSUS	Horizontal wind speed systematic uncertainty	Feet/second
16	HWSUN	Horizontal wind speed noise or fluctuation uncertainty	Feet/second

[1]All quantities are real variables one word in length.

Table 4-2. Format of LAIRS Meteorological Data Tape (2 of 2)

WORD	SYMBOL	DESCRIPTION	UNITS
17	VWSUN	Vertical wind speed noise or fluctuation uncertainty	Feet/second
18	HWDUS	Horizontal wind direction systematic uncertainty	Degrees
19	HWDUN	Horizontal wind direction noise or fluctuation uncertainty	Degrees
20		Spare	--

those listed in Section 4.1. The information on these cards will include the following:

- Model to be used (default, fitted, or interpolation)
- Type of calculation profile (ENTREE Program trajectory, or Local Atmospheric Profile, or both)
- Decision to rebuild permanent files

Other possible options and the models to which they apply are summarized in Table 4.3.

Also given on keyword cards will be specifics related to various options (such as LAP location). A set of station cards specifying latitudes and longitudes of stations supplying meteorological profiles, together with the number of profiles supplied by each station, will be required. Finally, the option to rebuild the permanent files will require special input similar to the meteorological observations (the exact nature of this input will depend upon the specific routines devised for model fitting).

4.2.4 PERMANENT AND WORKING FILES

As mentioned in Section 4.1, it will be necessary to maintain both permanent files, which are associated with default model parameters, and working files, which are associated with adjusted model parameters, for the operation of LAIRS. The permanent files will be accessed by the model-fitting routines only. These routines will create the working files, which will be accessed by the parameter calculation routines. When the default model is requested, the model-fitting routines will take the appropriate information from the permanent files and write it to the working files unaltered. The content of the files will be described in the following sections.

Table 4-3. Options Related to Model Choice

OPTION \ MODEL	DEFAULT	FITTED	INTERPOLATED
Altitude region in which to use model (default = entire)		✓	✓
Number of default data points to be added between Z1 and Z2 (default = none)		✓	
T, P, ρ fitting done independently (default) or P and ρ derived from T		✓	
Method to be used in joining Jacchia-Roberts to lower atmosphere	✓		
Inclusion of wind (default = yes - empirical)	✓	✓	✓
Use of analytic wind		✓	
Use of diurnal and semidiurnal variations and latitude gradients	✓	✓	✓

4.2.4.1 PERMANENT FILES

For the lower atmosphere, the permanent files will consist of several sets of polynomial coefficients representing the vertical distribution of temperature, pressure, and density for each month of the year. Horizontal wind components and latitude gradients of the atmospheric parameters will be tabulated on the files at 5-kilometer intervals for each month. Diurnal and semidiurnal variation coefficients will also be provided, but they will be identical for all months.

The Jacchia-Roberts model recommended for the upper atmosphere will require three coefficients (see Section 3.2). These will not have to be tabulated for each month. Additionally, the Jacchia-Roberts model requires three other files that are not, strictly speaking, permanent, but are also not derived from the meteorological observation files. These are the 3-hour geomagnetic planetary index (K_p) file, the 10.7-centimeter solar flux ($F_{10.7}$) file, and a file consisting of an 81-day running average of $F_{10.7}$ ($\bar{F}_{10.7}$), centered on the day of interest. These files must have new values added periodically, but once new values are added, they remain on the files permanently.

4.2.4.2 WORKING FILES

The working files for the upper and lower atmospheric models will contain exactly the same parameters as the permanent files, except that the working files will be produced by the model-adjustment software using the meteorological input data and the fitting processes discussed in Section 3. There will be no working files corresponding to the Jacchia-Roberts K_p, $F_{10.7}$, and $\bar{F}_{10.7}$ files.

The data contained in the working files are summarized in Table 4-4. The content and format of the permanent files will be identical to that of the working files, except that there will be 12 sets of permanent files (one for each month).

Table 4-4. Contents of LAIRS Permanent[1] and Working Files

LOWER ATMOSPHERE:
Three sets of polynomial coefficients for each of T, P, and ρ (0-25, 25-65, and 65-110 kilometers)
Tabulated winds U and V (0-110 kilometers)
Tabulated diurnal and semidiurnal coefficients for each of T, P, ρ, U, and V (0-110 kilometers)
Tabulated latitude gradients for each of T, P, ρ, U, and V (0-110 kilometers)
UPPER ATMOSPHERE:
Jacchia-Roberts coefficients[2] T_∞, T_1^B, and G_1^B
Tabulated wind U and V (110-130 kilometers)
Geomagnetic index[3] - K_p
Solar flux[3] - $F_{10.7}$
Average solar flux[3] - $\bar{F}_{10.7}$

[1]Permanent files will consist of 12 monthly sets of default values for the quantities tabulated here.

[2]The Jacchia-Roberts model includes diurnal, latitude, and annual effects. Only one set of default values will be required.

[3]K_p, $F_{10.7}$, and $\bar{F}_{10.7}$ need to exist only on permanent files.

4.3 MATHEMATICAL SPECIFICATIONS

Mathematical details necessary for the LAIRS implementation will be presented in this section. The description of the default atmospheric model is given in Section 4.3.1, followed by the discussion of fitting procedures in Section 4.3.2. Section 4.3.3 contains a summary of the computational procedures for various atmospheric parameters.

4.3.1 DEFAULT ATMOSPHERIC MODEL

The default atmospheric model for LAIRS consists of three parts: the Edwards Air Force Base Reference Atmosphere from the ground to approximately 25 kilometers, the Cospar International Reference Atmosphere (CIRA 1972) from 25 kilometers to 110 kilometers, and the Jacchia-Roberts atmospheric model above 120 kilometers.*

The Jacchia-Roberts atmospheric model determines the atmospheric mass density, ρ, and the number density of individual species, n_i, using the following two equations:

$$\frac{d}{dZ}(\ln \rho) = \frac{d}{dZ}\left(\ln \frac{\overline{M}}{T}\right) - \frac{\overline{M} g}{R^* T} \quad : \quad Z \leq 100 \text{ Km} \qquad (4\text{-}1)$$

$$\frac{d}{dZ}(\ln n_i) = -(1+\alpha_i)\frac{d}{dZ}(\ln T) - \frac{M_i g}{R^* T} \quad : \quad Z > 100 \text{ Km} \qquad (4\text{-}2)$$

where α_i = thermal diffusion coefficient of the species i

M_i = molecular weight of the species i

$\overline{M}$ = mean molecular weight

g = gravitational acceleration

R^* = universal gas constant

*An interpolation scheme will be used between 110 and 120 kilometers.

The first equation given above is the barometric equation and applies to a region of the homogeneously mixed atmosphere below 100 kilometers and the second equation is the diffusion equation for the number density of each individual species and applies to the atmosphere above approximately 100 kilometers, where the lighter species separate from the heavier species by the process of molecular diffusion.

The temperature, T, in Equations (4-1) and (4-2) has to be known as a function of Z. Temperature-height profiles were empirically obtained in the Jacchia 1971 model and will be slightly modified according to the formulation given by Roberts so that the density equations can be integrated analytically (References 15 and 18).

The temperature profile to be used in the Jacchia-Roberts atmospheric density model takes the form of a fourth-order polynomial for heights from 90 kilometers to 125 kilometers and an exponential function of Z for heights above 125 kilometers

$$T(Z) = T_x + (T_x - T_0) \sum_{n=1}^{4} a_n (Z - Z_x)^n \qquad (4\text{-}3)$$

This equation gives temperatures between Z_0 and Z_x, and the coefficients a_n are determined from the following conditions:

$$\begin{aligned}
T(Z_0) &= T_0 \text{ : minimum temperature} \\
T(Z_x) &= T_x \text{ : temperature at inflection point} \\
\left(\frac{dT}{dZ}\right)_{Z=Z_0} &= 0 \\
\left(\frac{dT}{dZ}\right)_{Z=Z_x} &= a_1(T_x - T_0) = 1.9\,\frac{(T_x - T_0)}{Z_x - Z_0} \text{ : an empirical relation}
\end{aligned} \qquad (4\text{-}4)$$

$$\left(\frac{d^2T}{dZ^2}\right)_{Z=Z_x} = 2a^2(T_x-T_0) = 0 \qquad (4-4)\ \text{(cont'd)}$$

The four coefficients a_i ($i = 1 \rightarrow 4$) can be expressed in terms of Z_0, Z_x, T_0, and T_x as follows:

$$\begin{aligned} a_1 &= 1.9/(Z_x - Z_0) \\ a_2 &= 0 \\ a_3 &= -1.7/(Z_x - Z_0)^3 \\ a_4 &= -0.8/(Z_x - Z_0)^4 \end{aligned} \qquad (4-5)$$

The values of Z_0 and Z_x are fixed at 90 kilometers and 125 kilometers, respectively. The value of T_0 was 183° K in the Jacchia 1971 model and was changed to 188° K in the Jacchia 1977 model. The quantity T_x is determined from the value of T_∞ (Reference 13)

$$T_x = a + bT_\infty + ce^{\bar{k}T_\infty} \qquad (4-6)$$

where $a = 371.6678$
$b = 0.0518806$
$c = -294.3505$
$\bar{k} = -0.00216222$

For heights above 125 kilometers, Roberts used the following function to define the temperature:

$$T(Z) = T_\infty - (T_\infty - T_x) \exp\left(-G_x \frac{Z - Z_x}{T_\infty - T_x} \cdot \frac{R_a + Z_x}{R_a + Z}\right) \quad (4-7)$$

where G_x = temperature gradient at Z_x

R_a = 6356.766 kilometers = mean radius of the Earth

A temperature profile defined by Equations (4-3) and (4-7) is continuous at $Z = Z_x$ regardless of the choice of G_x. The temperature gradient will be continuous at $Z = Z_x$ if $G_x = 1.9(T_x - T_0)/(Z_x - Z_0)$. However, in the Jacchia-Roberts density model implemented in GTDS, G_x was determined as a function of T_∞ such that the resulting density profiles obtained using Roberts' temperature profiles gave the best least-squares fit to Jacchia's tabulated density data. In this case, the temperature gradient is not continuous at $Z = Z_x$.

In addition to temperature profiles, Equations (4-1) and (4-2) require a knowledge of g(z) and $\overline{M}(z)$. The following expressions were used for these quantities:

$$g(Z) = g_0 R_a^2 / (Z + R_a)^2 \quad (4-8)$$

where g_0 = 9.80665 meters per second^2, and

$$\overline{M}(Z) = \sum_{n=0}^{6} C_n (Z - 90)^n \; : \; 90 < z < 100 \quad (4-9)$$

$$(Z \text{ in Km})$$

Numerical values in this equation are given in Reference 14. Roberts analytically integrated Equations (4-1) and (4-2) using temperature profiles given by Equations (4-3) and (4-7); the gravitational acceleration, g(z); and the mean molecular weight, $\overline{M}(Z)$. The quantities g(Z) and $\overline{M}(Z)$ are defined by Equations (4-8) and (4-9), respectively. The solutions obtained by Roberts, however, contain rather lengthy algebraic expressions and will not be given in this report. (See References 15 and 18 for further details.)

The computation of T_∞ is described in Section 2.2. Discussion of various other corrections included in the Jacchia-Roberts density model can be found in References 13 and 15.

The Jacchia-Roberts atmospheric density model will be used for heights above 120 kilometers and the CIRA model for heights below 110 kilometers. For heights between 110 kilometers and 120 kilometers, an appropriate interpolation scheme will be used for each atmospheric parameter. A four-point Langrange interpolation method will be used for temperatures and a two-point exponential interpolation scheme for densities and pressures. The latter interpolation procedure is defined as

$$\rho = \rho_A \exp\left\{\frac{\ln \rho_A - \ln \rho_B}{Z_A - Z_B}\,(Z - Z_A)\right\} \tag{4-10}$$

which gives $\rho = \rho_A$ at $Z = Z_A$ and $\rho = \rho_B$ at $Z = Z_B$.

An alternative method of connecting the CIRA model to the Jacchia-Roberts model involves readjusting some of the parameters that determine the structure of the Jaccia-Roberts model. Let Z_1 be the boundary between the two regions described by the CIRA and Jacchia-Roberts models, respectively. Z_1 can assume any value between Z_o (90 kilometers) and Z_x

(125 kilometers), excluding Z_x. Two parameters, T_o and ρ_o, in the Jacchia-Roberts model can be readjusted so that the various atmospheric parameters will be continuous at $Z = Z_1$. Let T_o' and ρ_o' be the newly adjusted values of these two parameters. Then, using Equation (4-3),

$$T_o' = T_x + \frac{T_x - T_{CIRA}(Z_1)}{\sum_{n=1}^{4} a_n (Z_1 - Z_x)^n}$$

For calculating the density parameter, the following simple scaling law will be sufficient.

$$\rho_o' = \rho_o \, \rho_{CIRA}(Z_1) / \rho_{JR}(Z_1)$$

where $\rho_{JR}(Z_1)$ should be calculated using T_o'.

When the temperature and density are continuous at $Z = Z_1$, the pressure will also be continuous, at least approximately. In this alternative method, there is no need for any interpolation scheme. The region above $Z = Z_1$ is described by the Jacchia-Roberts model and the region below $Z = Z_1$ is described by the CIRA model.

If Z_1 is chosen to be near 90 kilometers, then it is more consistent and advantageous to completely redetermine Z_o, T_o, and ρ_o, i.e., the position, temperature, and density of the last temperature minimum, from the default CIRA temperature profile. In this case, Z_o will be used in place of Z_1.

The CIRA 1972 model will be used in LAIRS to compute various atmospheric parameters for heights between 25 and 110 kilometers, and the ERA model will cover the region from the ground up to 25 kilometers. Temperatures, densities, and pressures near 30 degrees north latitude will be computed from a set of polynomials defined for each month of the year.

The form of these polynomials was defined in Equations (3-4) and (3-6) in Sections 3.2.1 and 3.2.2, and the corresponding coefficients will be stored in the default atmospheric file. In addition to these coefficients, the default atmospheric file will also contain latitude gradients of various atmospheric parameters near 30 degrees north latitude and will contain amplitudes and phases of the diurnal and semidiurnal variations.

4.3.2 DEFINITION OF FITTING PROCEDURES

4.3.2.1 Diurnal, Semidiurnal, and Latitudinal Variations

A new set of amplitudes and phases of the diurnal and semidiurnal variations can be determined if observed data have enough spread in local solar time. Similarly, a new set of latitude gradients of atmospheric parameters can be determined if the observed data have enough spread in latitude.

The ith vertical profile in the original meteorological measurements will be denoted as $\{\xi^i(Z^i_m, \theta_i, t_i) \mid m = 1 \sim M^i_0\}$. The label i belongs to a set J_0 which contains all labels of the profiles available in the original meteorological data, and M^i_0 is the total number of meteorological measurements included in the ith profile. The quantity ξ is used to denote an atmospheric parameter (temperature, pressure, or density).

The first step in finding new diurnal and semidiurnal variations involves computing $\xi^i(Z^R_m, \theta_R, t_i)$ from $\xi^i(Z^i_m, \theta_i, t_i)$, using the default latitude gradients of ξ and an appropriate interpolation scheme for Z. The parameters θ_R and $\{Z^R_m\}$ denote a reference latitude and a set of reference vertical points, respectively.

If $\{\xi^i(Z_m^R, \theta_i, t_i) \mid m = 1 \sim M_R^i\}$ denotes the interpolated profile, then the latitude translation is performed on this interpolated profile to obtain $\xi^i(Z_m^R, \theta_R, t_i)$. This latitude translation is given as

$$\xi^i(Z_m^R, \theta_R, t_i) = \xi^i(Z_m^R, \theta_i, t_i) + g(Z_m^R, \theta_i, t_i)\,(\theta_R - \theta_i) \qquad (4\text{-}11)$$

where $g(Z_m, \theta_i, t_i)$ denotes the latitude gradient of ξ at (Z_m, θ_i, t_i).

In the latitude translation, the second-order and higher order terms in $(\theta_R - \theta_i)$ and the local solar time dependence of g will be neglected. Within this approximation, $g(Z_m, \theta_i, t_i)$ can be replaced by $g_0(Z_m)$, the default gradient at some reference latitude. Interpolating ξ from $\{Z_m^i\}$ to $\{Z_m^R\}$, a three-point Lagrange method will be sufficient.

The interpolation scheme should be used only in the neighborhood of real observation points. The number of measurements at Z_m^R with different local solar times may not be a constant, but may depend upon Z_m^R. That is, at different heights, observation data might have different distributions in local solar time. This does not present any real problem as far as determining new diurnal and semidiurnal variations, since these variations are determined at each height Z_m^R independently.

Using this set of profiles defined at θ_R and $\{Z_m^R\}$, a new set of diurnal and semidiurnal amplitudes and phases will be determined as follows. First, $\xi(Z_m^R, \theta_R, t)$ is assumed to have the following t-dependence:

$$\xi(Z_m^R, \theta_R, t) = A_0\{1 + R_1 \cos(\omega t + \beta_1) + R_2 \cos(2\omega t + \beta_2)\} \qquad (4\text{-}12)$$

where ω is the rotational speed of the Earth. The diurnally averaged amplitude, A_0; the diurnal parameters, R_1 and β_1; and the semidiurnal parameters, R_2 and β_2, are functions of Z_m^R and θ_R only and can be determined using the set of profiles constructed at θ_R and $\{Z_m^R\}$. The set of equations that determines these parameters is given by

$$\xi^i(Z_m^R, \theta_R, t_i) = A_0\left\{1 + R_1\cos(\omega t_i + \beta_1) + R_2\cos(2\omega t_i + \beta_2)\right\} \quad (i \in J) \tag{4-13}$$

As noted earlier, the number of profiles, N_J, contained in J could be a function of Z_m^R. If $N_J \gg 5$, the five parameters A_0, R_1, R_2, β_1, β_2 can be obtained by least-squares fitting procedures. If $N_J = 5$, these parameters can be algebraically solved for. If $N_J < 5$, only a subset of these parameters can be determined.

However, N_J is not the only factor that determines the solvability of Equation (4-13). There should also be enough spread in local solar time. If all the profiles belonging to J are clustered within a couple of hours, not all of these parameters can be accurately solved for. In this case, a partial readjustment of these parameters will be carried out.

After these diurnal and semidiurnal parameters are determined, new latitude gradients will be estimated. This involves computing $\xi^i(Z_m^R, \theta_i, t_R)$ from $\xi^i(Z_m^R, \theta_i, t_i)$, using the newly determined diurnal and semidiurnal parameters as follows:

$$\xi^i(Z_m^R, \theta_i, t_R) = \xi^i(Z_m^R, \theta_i, t_i) \cdot D(t_i, t_R) \quad (i \in J) \tag{4-14}$$

$$\mathcal{D}(t_i, t_R) = \frac{1 + R_1 \cos(\omega t_R + \beta_1) + R_2 \cos(2\omega t_R + \beta_2)}{1 + R_1 \cos(\omega t_i + \beta_1) + R_2 \cos(2\omega t_R + \beta_2)} \qquad (4\text{-}15)$$

If the set of profiles, $\{\xi^i(Z_m^R, \theta_i, t_R)\}$, has enough spread in latitude in the neighborhood of the reference latitude, θ_R, the θ-dependence of ξ can be determined from

$$\{\xi^i(Z_m^R, \theta_i, t_R) \mid i \in J\} .$$

The θ-dependence of ξ is defined as

$$\xi(Z_m^R, \theta, t_R) = \xi(Z_m^R, \theta_R, t_R) + g(Z_m^R, \theta_R, t_R)\cdot(\theta - \theta_R) \qquad (4\text{-}16)$$

The two quantities $\xi(Z_m^R, \theta_R, t_R)$ and $g(Z_m^R, \theta_R, t_R)$ will be determined from the following set of equations:

$$\xi^i(Z_m^R, \theta_i, t_R) = \xi(Z_m^R, \theta_R, t_R) + g(Z_m^R, \theta_R, t_R)(\theta_i - \theta_R) \qquad (4\text{-}17)$$

$$(i \in J)$$

If the number of points in J, N_J, is greater than 2, least-squares fitting procedures can be used to find $\xi(Z_m^R, \theta_R, t_R)$ and $g(Z_m^R, \theta_R, t_R)$. If $N_J = 2$, these two quantities can be obtained algebraically.

The composite reference profile defined in Equation (3-2) can then be built from the original set of data as follows:

$$\xi^i(Z_m^i, \theta_R, t_R) = \mathcal{D}(t_i, t_R)\, \xi^i(Z_m^i, \theta_R, t_i) \qquad (4\text{-}18)$$

$$\xi^i(Z_m^i, \theta_R, t_i) = \xi^i(Z_m^i, \theta_i, t_i) + g(Z_m^i, \theta_i, t_i)(\theta_R - \theta_i) \quad (4\text{-}19)$$

Here $D(t_i, t_R)$ and $g(Z_m^i, \theta_i, t_i)$ are the new diurnal, semidiurnal, and latitudinal variations determined above. It should be noted that D and g are defined at $\{Z_m^R\}$. An appropriate interpolation scheme can be used to compute D and g at $\{Z_m^i\}$.

The composite reference profile to be used in the vertical fitting procedures takes the following form:

$$\left\{ \xi^i(Z_m^i, \theta_R, t_R) \mid m = 1 \sim M_o^i \; ; \; i = 1 \sim N_{J_o} \right\}$$

The number of observation points in this super set is

$$M = \sum_{i=1}^{N_{J_o}} M_o^i$$

Using M, the entire set can be written as

$$\mathcal{P}(\theta_R, t_R) = \left\{ \xi(Z_m, \theta_R, t_R) \mid m = 1 \sim M \right\} \quad (4\text{-}20)$$

4.3.2.2 Vertical Profiles

Model vertical profiles for temperature, density, and pressure use the Jacchia-Roberts density model in the uppermost region above 125 kilometers and a set of polynomials for heights below 125 kilometers. To define these functions, it is convenient to use a step function defined as follows:

$$\begin{aligned} h(\zeta) &= 1 \text{ if } \zeta > 0 \\ &= 0 \text{ if } \zeta < 0 \end{aligned} \quad (4\text{-}21a)$$

$$
\begin{aligned}
H_{ij}(Z) &= h(Z-Z_i)\ h(Z_j-Z) \\
&= 1 \quad \text{if } Z_i < Z < Z_j \\
&= 0 \quad \text{otherwise}
\end{aligned}
\tag{4-21b}
$$

where Z_i = boundary between two consecutive regions
Z_0 = 2500 kilometers (upper boundary of the Jacchia-Roberts model)
Z_4 = 0 (ground)

In particular, $H_{10}(Z) = h(Z-Z_1)$ and $H_{43}(Z) = h(Z_3-Z)$.

Then a model vertical profile can be written as

$$F(Z) = \sum_{i=1}^{4} H_{i\,i-1}(Z)\, F_i(Z) \tag{4-22}$$

In this equation, the $F_i(Z)$ ($i=1\rightarrow4$) for temperature, pressure, and density are defined in Equations (3-3) through (3-7). For convenience, these equations are repeated here:

Temperature

$$
\begin{aligned}
F_1(Z) &= T_\infty - (T_\infty - T_1^B)\, e^{-E(Z)} \\
E(Z) &= G_1^B \frac{Z - Z_1^B}{T_\infty - T_1^B} \cdot \frac{R_a + Z_1^B}{R_a + Z}
\end{aligned}
\tag{4-23}
$$

$$F_i(Z) = F_{i-1}^B + \sum_{n=1}^{N_i} C_{in}(Z - Z_{i-1}^B)^n \quad (i = 2 \sim 4) \tag{4-24}$$

$$F_1^B = T_1^B$$

Density

$$F_1(Z) = -\ln(\rho_{JR}/\rho_o) \tag{4-25}$$

Pressure

$$F_1(Z) = -\ln(p_{JR}/p_o) \tag{4-26}$$

where

$$p_{JR} = R^* T \sum_{\ell} n_\ell / N_A \quad (Z > 100 \text{ Km})$$

$$= R^* T \rho_{JR} / \overline{M}(Z) \quad (Z \leq 100 \text{ Km})$$

The $F_i(Z)$ ($i=2 \rightarrow 4$) for pressure and density take the same form as these for the temperature. The coefficients C_{in} ($n=1 \rightarrow N_i$; $i=2 \rightarrow 4$) and the boundary values T_1^B, T_∞, and G_1^B, can be readjusted through least-squares fitting procedures. A model vertical profile defined by these N unknown parameters is fitted to a reference profile of observation data defined in Section 4.3.2.1. These unknown parameters will be collectively denoted as $\bar{S}$, an N-dimensional vector, and F(Z) will be written as $F(Z,\bar{S})$ to explicitly indicate the dependence of F(Z) on $\bar{S}$.

The reference observation profile is given as

$$\mathcal{P}(\theta_R, t_R) = \{ \xi(Z_m, \theta_R, t_R) \mid m = 1 \sim M \} \qquad (4\text{-}20)$$

where ξ represents an atmospheric parameter and M is the total number of meteorological measurements included in the set. The quantities θ_R and t_R denote a reference latitude and a reference local solar time, respectively. In the following, an abbreviated notation $\xi(Z_m)$ will often be used in place of $\xi(Z_m, \theta_R, t_R)$.

The loss function to be minimized is defined as

$$Q(\bar{S}) = \sum_{m=1}^{M} w_m [F(Z_m, \bar{S}) - \xi(Z_m)]^2 \qquad (4\text{-}27)$$

where w_m is the weighting factor of the mth observation. Using matrix notation, this equation can be written as

$$Q(\bar{S}) = [\bar{F}(\bar{S}) - \bar{\xi}]^T W [\bar{F}(\bar{S}) - \bar{\xi}] \qquad (4\text{-}28)$$

where $\bar{F}$ and $\bar{\xi}$ are M-dimensional column vectors with $F(Z_m, \bar{S})$ and $\xi(Z_m)$ as their mth components, respectively, and W is an M×M diagonal matrix with w_m as its mth diagonal element. It should be noted that, in Equation (4-28), $\bar{\xi}$ should be replaced by $\{-\ln(\xi(Z_m)/\xi_0\}$ in the case of pressure or density.

In general, $\overline{F}(\overline{S})$ is not a linear function of $\overline{S}$. The linearized loss function, $Q_L(\overline{S})$ can be obtained using the Taylor expansion of $\overline{F}(\overline{S})$ as follows:

$$\begin{aligned} \overline{F}(\overline{S}) &= \overline{F}(\overline{S}_0) + B\Delta\overline{S} \\ B &= (\partial\overline{F}/\partial\overline{S})_{\overline{S}=\overline{S}_0} \quad : M \times N \text{ matrix} \\ \Delta\overline{S} &= \overline{S} - \overline{S}_0 \end{aligned} \tag{4-29}$$

$$Q_L(\Delta\overline{S}) = (B\Delta\overline{S} - \Delta\overline{\xi})^T W (B\Delta\overline{S} - \Delta\overline{\xi}) \tag{4-30}$$

where

$$\Delta\overline{\xi} = \overline{\xi} - \overline{F}(\overline{S}_0)$$

The value of $\Delta\overline{S}$ that minimizes $Q_L(\Delta\overline{S})$ is given by

$$\Delta\overline{S} = (B^T W B)^{-1} B^T W \Delta\overline{\xi} \tag{4-31}$$

From this $\Delta\overline{S}$, $\overline{S}$ can be determined as follows:

$$\overline{S} = \overline{S}_0 + \Delta\overline{S} \tag{4-32}$$

When $\bar{F}(\bar{S})$ is not a linear function of $\bar{S}$, this process will repeat with $\bar{S}$ as a new $\bar{S}_0$. If $\bar{F}(\bar{S})$ is a linear function of $\bar{S}$, i.e., $\bar{F}(\bar{S}) = \bar{F}_0 + B\bar{S}$, then $\bar{S}$ which minimizes $Q(\bar{S})$ (Equation (4-28)) is given by

$$\bar{S} = (B^T W B)^{-1} B^T W \Delta\bar{\xi} \qquad (4\text{-}33)$$

where

$$\Delta\bar{\xi} = \bar{\xi} - \bar{F}_0$$

The quantity B is calculated as follows:

$$B = \left(\partial\bar{F} / \partial\bar{S} \right)$$

$$B_{mn} = \left(\partial F(Z_m, \bar{S}) / \partial S_n \right) \qquad (4\text{-}34)$$

Using Equation (4-22), B_{mn} can be written in terms of $F_i(Z,\bar{S})$, i.e.,

$$B_{mn} = \sum H_{i\,i-1}(Z_m) \left(\partial F_i(Z_m, \bar{S}) / \partial S_n \right) \qquad (4\text{-}35)$$

The solve-for parameter array, $\bar{S}$, is defined as follows:

$$
\begin{aligned}
\bar{S}^T &= (\bar{C}_1^T, \bar{C}_2^T, \bar{C}_3^T, \bar{C}_4^T) \\
\bar{C}_1^T &= (T_1^B, G_1^B, T_\infty) \\
\bar{C}_i^T &= (C_{i1}, C_{i2}, \cdots, C_{iN_i}) \quad (i = 2 \sim 4)
\end{aligned}
\tag{4-36}
$$

Temperature expressions given in Equations (4-23) and (4-24) can be written more explicitly as follows:

$$F_1(Z) = T_\infty - (T_\infty - T_1^B)\, e^{-E(Z)} \tag{4-37}$$

$$E(Z) = G_1^B \frac{Z - Z_1^B}{T_\infty - T_1^B} \cdot \frac{R_a + Z_1^B}{R_a + Z} \tag{4-38}$$

$$F_2(Z) = F_1^B + \sum_{n=1}^{N_2} C_{2n} (Z - Z_1^B)^n \tag{4-39}$$

$$
\begin{aligned}
F_3(Z) = F_1^B &+ \sum_{n=1}^{N_2} C_{2n} (Z_2^B - Z_1^B)^n \\
&+ \sum_{n=1}^{N_3} C_{3n} (Z - Z_2^B)^n
\end{aligned}
\tag{4-40}
$$

$$F_4(Z) = F_1^B + \sum_{n=1}^{N_2} C_{2n} (Z_2^B - Z_1^B)^n + \sum_{n=1}^{N_3} C_{3n} (Z_3^B - Z_2^B)^n + \sum_{n=1}^{N_4} C_{4n} (Z - Z_3^B)^n \qquad (4-41)$$

where $F_1^B = T_1^B$

From these temperature expressions, the partial derivatives of temperature with respect to S can easily be obtained, i.e.,

$$\frac{\partial F_1}{\partial S_1} = (1 + E(Z)) e^{-E(Z)}$$

$$\frac{\partial F_1}{\partial S_2} = (Z - Z_1^B) \frac{R_a + Z_1^B}{R_a + Z} e^{-E(Z)} \qquad (4-42)$$

$$\frac{\partial F_1}{\partial S_3} = 1 - (1 + E(Z)) e^{-E(Z)}$$

$$\frac{\partial F_1}{\partial S_n} = 0 \qquad (n > 3)$$

$$\frac{\partial F_2}{\partial C_{1n}} = \delta_{1n} \quad (n = 1 \sim 3)$$

$$\frac{\partial F_2}{\partial C_{2n}} = (Z - Z_1^B)^n \quad (n = 1 \sim N_2) \tag{4-43}$$

$$\frac{\partial F_2}{\partial C_{in}} = 0 \quad (i = 3, 4)$$

$$\frac{\partial F_3}{\partial C_{1n}} = \delta_{1n} \quad (n = 1 \sim 3)$$

$$\frac{\partial F_3}{\partial C_{2n}} = (Z_2^B - Z_1^B)^n \quad (n = 1 \sim N_2) \tag{4-44}$$

$$\frac{\partial F_3}{\partial C_{3n}} = (Z - Z_2^B)^n \quad (n = 1 \sim N_3)$$

$$\frac{\partial F_3}{\partial C_{4n}} = 0$$

$$\frac{\partial F_4}{\partial C_{1n}} = \delta_{1n} \quad (n = 1 \sim 3)$$

$$\frac{\partial F_4}{\partial C_{2n}} = (Z_2^B - Z_1^B)^n \quad (n = 1 \sim N_2) \tag{4-45}$$

$$\frac{\partial F_4}{\partial C_{3n}} = (Z_3^B - Z_2^B)^n \qquad (n = 1 \sim N_3)$$

$$\frac{\partial F_4}{\partial C_{4n}} = (Z - Z_3^B)^n \qquad (n = 1 \sim N_4) \tag{4-45 (Cont'd)}$$

In these equations, δ_{nm} denotes the Kronecker delta.

In the computation of B_{mn}, Z will assume the value of Z_m. It should be noted that the $(\partial F_i/\partial S_n)$ $(i=2\rightarrow 4)$ are independent of $\bar{S}$. The partial derivative $(\partial F_1/\partial \bar{C}_1)$ is the only partial derivative that is dependent on $\bar{S}$. When the lower atmosphere is readjusted independently of the upper atmosphere, the problem becomes a linear one and the solution will be given by Equation (4-33).

For densities and pressures, a similar set of partial derivatives can be derived. In this case, $\bar{C}_1^T$ is redefined as

$$\bar{C}_1^T = (T_1^B, G_1^B, T_\infty, \rho_0) \tag{4-46}$$

where ρ_0 is the density at Z = 90 kilometers. The variation of ρ_0 will give an overall rescaling of densities and pressures. The $F_1(Z)$ for the density and pressure is given in Equations (4-25) and (4-26), respectively, i.e.,

Density: $$F_1(Z) = -\ln(\rho_{JR}/\rho_0)$$

Pressure: $$F_1(Z) = -\ln(p_{JR}/p_0)$$

Density: $$\frac{\partial F_1}{\partial \bar{C}_1} = -\frac{1}{\rho_{JR}}\left(\frac{\partial \rho_{JR}}{\partial T_1^B}, \frac{\partial \rho_{JR}}{\partial G_1^B}, \frac{\partial \rho_{JR}}{\partial T_\infty}, \frac{\partial \rho_{JR}}{\partial \rho_0}\right) \quad (4\text{-}47)$$

Pressure: $$\frac{\partial F_1}{\partial \bar{C}_1} = -\frac{1}{P_{JR}}\left(\frac{\partial P_{JR}}{\partial T_1^B}, \frac{\partial P_{JR}}{\partial G_1^B}, \frac{\partial P_{JR}}{\partial T_\infty}, \frac{\partial P_{JR}}{\partial \rho_0}\right) \quad (4\text{-}48)$$

Since ρ_0 is an overall scaling factor, $(\partial\rho_{JR}/\partial\rho_0)$ and $(\partial p_{JR}/\partial\rho_0)$ are equal to ρ_{JR}/ρ_0 and p_{JR}/ρ_0, respectively. The remaining partial derivatives are the same as those given in Equations (4-42) through (4-45), with the following exceptions:

$$\frac{\partial F_i}{\partial \bar{C}_1} = \left(\frac{\partial F_1}{\partial \bar{C}_1}\right)_{Z=Z_1^B} \quad \text{(for } i=2\rightarrow 4\text{)} \quad (4\text{-}49)$$

The right-hand side of this equation is given by Equations (4-47) and (4-48) for density and pressure, respectively. If the lower atmosphere is readjusted independently of the upper atmosphere, then F_1^B will become an adjustable parameter and the same form of partial derivatives derived for the temperature of the lower atmosphere can be used.

The computation of $(\partial F_1/\partial\bar{C}_1)$ defined in Equations (4-47) and (4-48) can be carried out analytically, but it involves lengthy algebraic expressions. It may be advantageous to calculate these partial derivatives numerically.

If only the lower atmosphere is readjusted independently of the upper atmosphere, the upper and lower parts of the atmosphere can be linked using an interpolation scheme. An alternative method would be partially readjusting the Jacchia-Roberts model using a new set of parameters associated with the lower boundary of the model, i.e., Z_0, ρ_0, and T_0 (the position, density, and temperature of the last temperature minimum near 90 kilometers). These parameters can easily be found from the fitted model lower atmosphere. The atmosphere above $Z = Z_o$ will then be described by the Jacchia-Roberts model, and the newly determined lower atmospheric model will describe the region below $Z = Z_o$.

4.3.3 COMPUTATION OF ATMOSPHERIC PARAMETERS

The final readjusted model vertical profile of an atmospheric parameter is given by Equation (4-22), i.e.,

$$F(z) = \sum_{i=1}^{4} H_{i\,i-1}(z) F_i(z)$$

This profile corresponds to a reference latitude, θ_R, and a reference local solar time, t_R. Thus, F(Z) can be written as $F(Z, \theta_R, t_R)$.

It is assumed that the position of the Shuttle is given by $(Z_s, \theta_s, \phi_s, \tau)$. First, the longitude, ϕ_s, and the time, τ, must be converted into a local solar time, t_s. Then, $F(Z_s, \theta_s, t_s)$ can be computed from the following equations, using $F(Z_s, \theta_R, t_R)$ and the diurnal, semidiurnal, and latitudinal variations derived in Section 4.3.2.1:

$$F(Z_s, \theta_s, t_s) = F(Z_s, \theta_s, t_R)\, D(t_R, t_s) \qquad (4\text{-}50)$$

$$F(Z_s, \theta_s, t_R) = F(Z_s, \theta_R, t_R) + g(Z_s, \theta_R, t_R)(\theta_s - \theta_R) \qquad (4\text{-}51)$$

where D and g are described in Section 4.3.2.1.

4.4 <u>OUTPUT</u>

4.4.1 ATMOSPHERIC PARAMETER USER FILE

The Atmospheric Parameter User File will consist of the input Shuttle trajectory (altitude, latitude, longitude, and time) together with the calculated values of the atmospheric parameters (temperature, pressure, density, and wind components) as determined by the models for each point on the trajectory. The file header record will indicate whether the default or fitted models were used in the calculations. Table 4-5 contains the format of this file.

4.4.2 ATMOSPHERIC PARAMETER OUTPUT REPORT

The Atmospheric Parameter Output Report will be a printed record of the information contained in the user file. It will be produced at the same time that the user file is produced. The contents of this report are the same as those displayed in Table 4-5.

4.4.3 LOCAL ATMOSPHERIC PROFILE REPORT

A report consisting of one or more vertical profiles of temperature, pressure, density, and wind components will be an output option available to the user. These profiles will be determined from the permanent or working files and will be reported at the latitude, longitude, and time the user has chosen. This choice will be limited in latitude to a region centered on 30 degrees north latitude because of the design of the models. The local atmospheric profile report will serve as a tool in judging the quality of the system's output. The information shown in Table 4-5 will be listed in the report.

Table 4-5. Contents of Atmospheric Parameter User File[1]

WORD	SYMBOL	DESCRIPTION	UNITS
1	LAT	Latitude	Degrees, + N
2	LON	Longitude	Degrees, + E to 360
3	ALT	Geodetic altitude	Kilometers
4	T	Time (GMT)	Hours, minutes, seconds
5	TE	Temperature	Degrees K
6	PR	Pressure	Millibars
7	D	Density	$Grams/cm^3$
8	U	North-south wind velocity	Meters/second, + N
9	V	East-west wind velocity	Meters/second, + E
10	WS	Total horizontal wind speed	Meters/second
11	WD	Direction wind is coming from relative to true north (0 degrees), increasing positively clockwise	Degrees
12	TEU	Estimated uncertainty in temperature	Degrees K
13	PRU	Estimated uncertainty in pressure	Millibars
14	DU	Estimated uncertainty in density	$Grams/cm^3$
15	UU	Estimated uncertainty in north-south wind	Meters/second
16	VU	Estimated uncertainty in east-west wind	Meters/second

[1]All quantities are real variables one word in length. A single record is 16 words long. One record will be produced for each point on the input ENTREE trajectory.

4.4.4 MODEL ADJUSTMENT REPORT

After the working files have been built, a model adjustment report will be printed. This report will contain statistical information concerning the fitting of the models, such as residuals, dispersion of the observations in time and space, and the number of observations on which the model adjustment was based.

4.5 ANALYSIS OF SOFTWARE REQUIREMENTS

This section consists of a set of data flow diagrams (Figures 4-1 through 4-9) and process specifications which form a structured analysis of LAIRS. The LAIRS software will be designed in accordance with this analysis. In addition, the software development will be undertaken in two distinct phases. In Phase 1, the model parameter calculation software and a set of default (permanent) files will be developed and delivered, allowing the user to test the system in its default mode. In Phase 2, the model adjustment software will be developed. Following the delivery of this software, the user will be able to utilize all aspects of LAIRS, including the processing of meteorological input data.

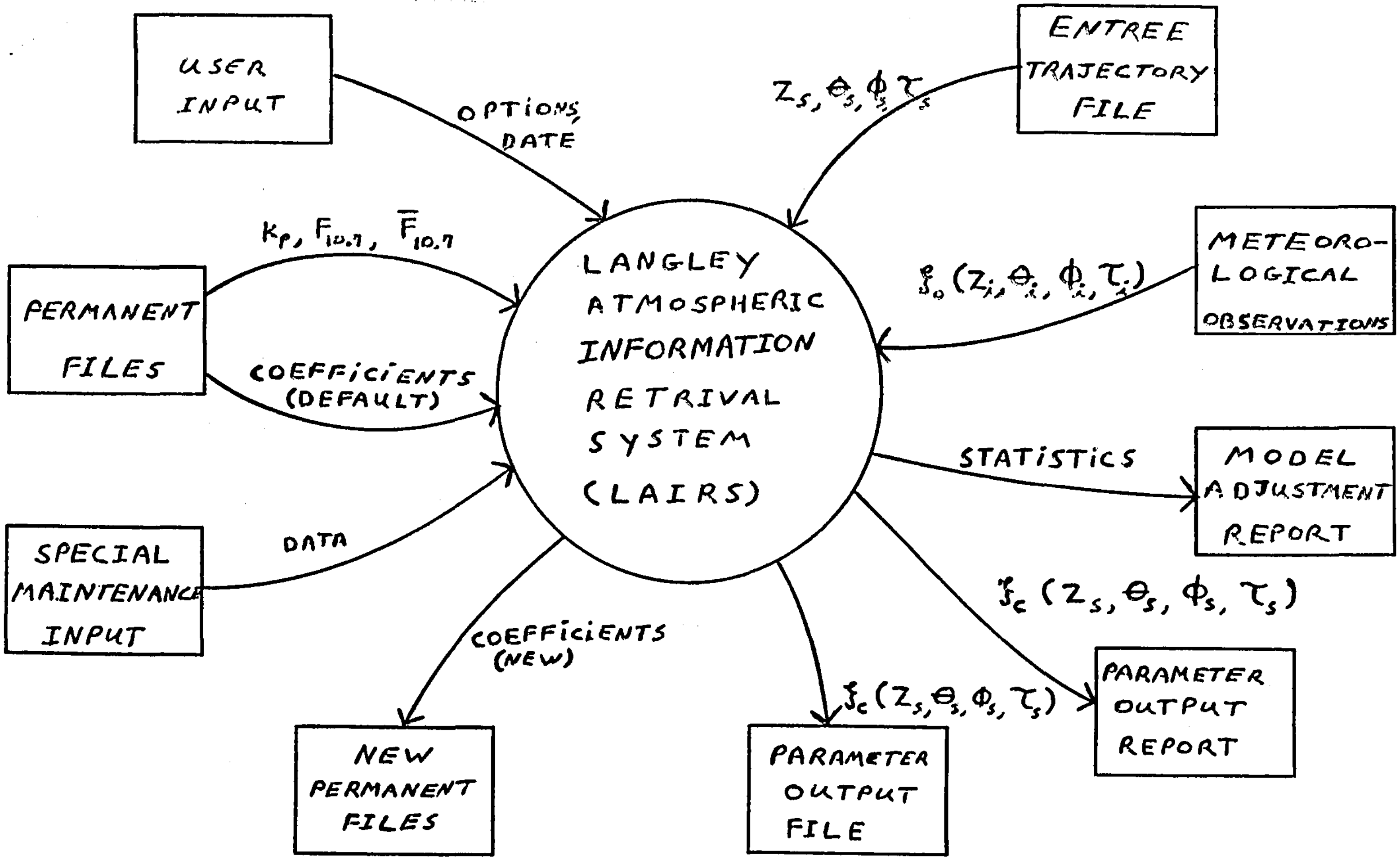

Figure 4-1. Context Diagram for LAIRS

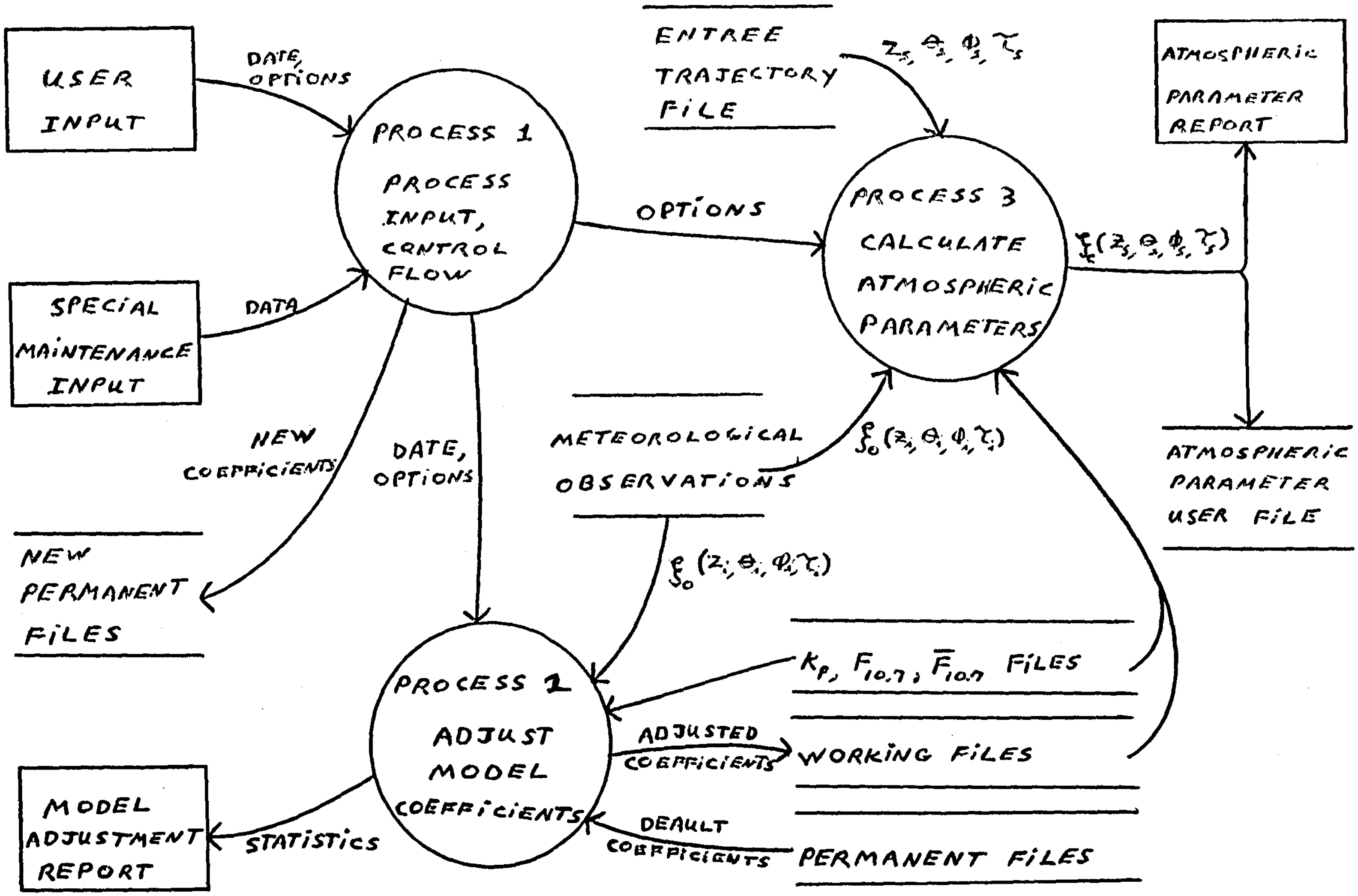

Figure 4-2. LAIRS Overall Design

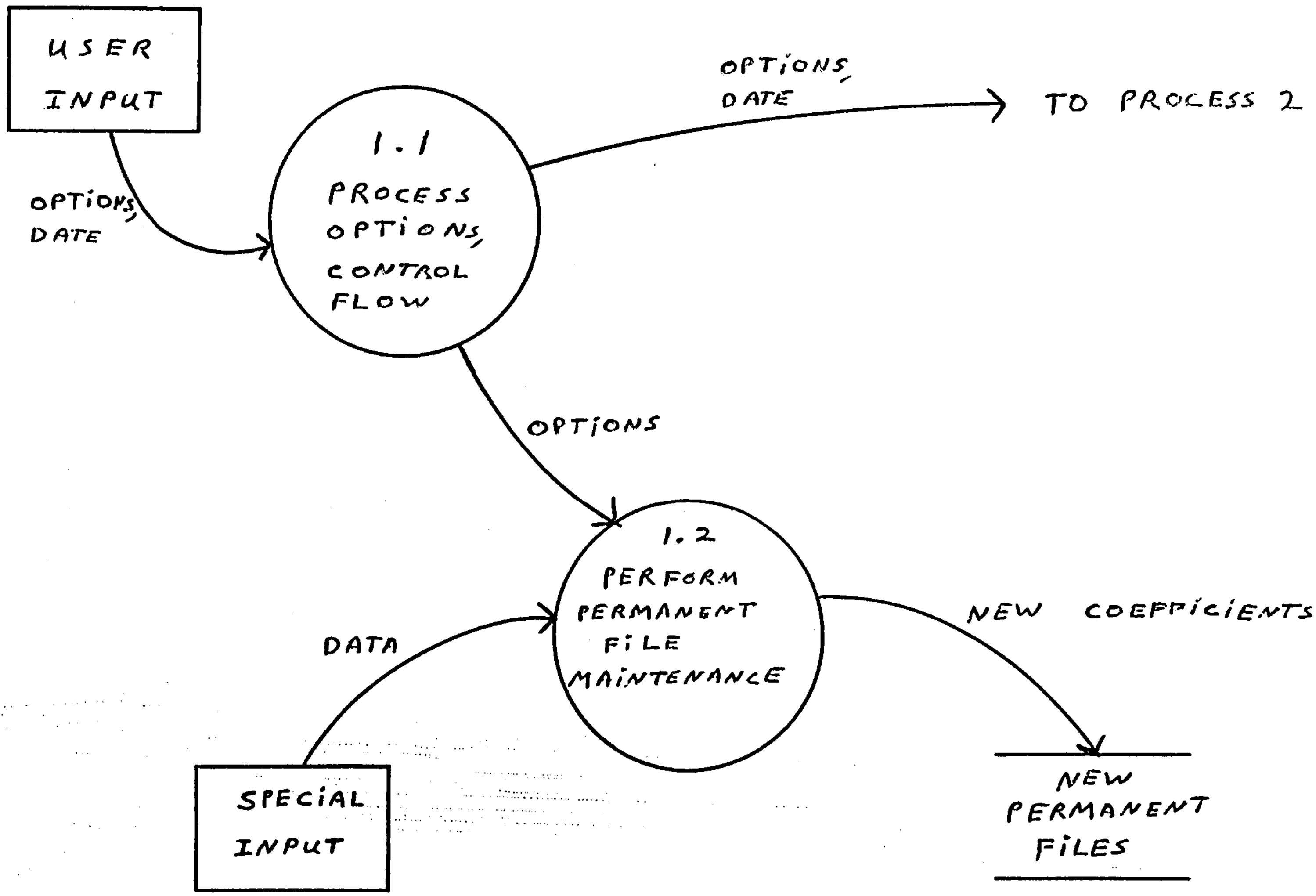

Figure 4-3. Process 1 Details

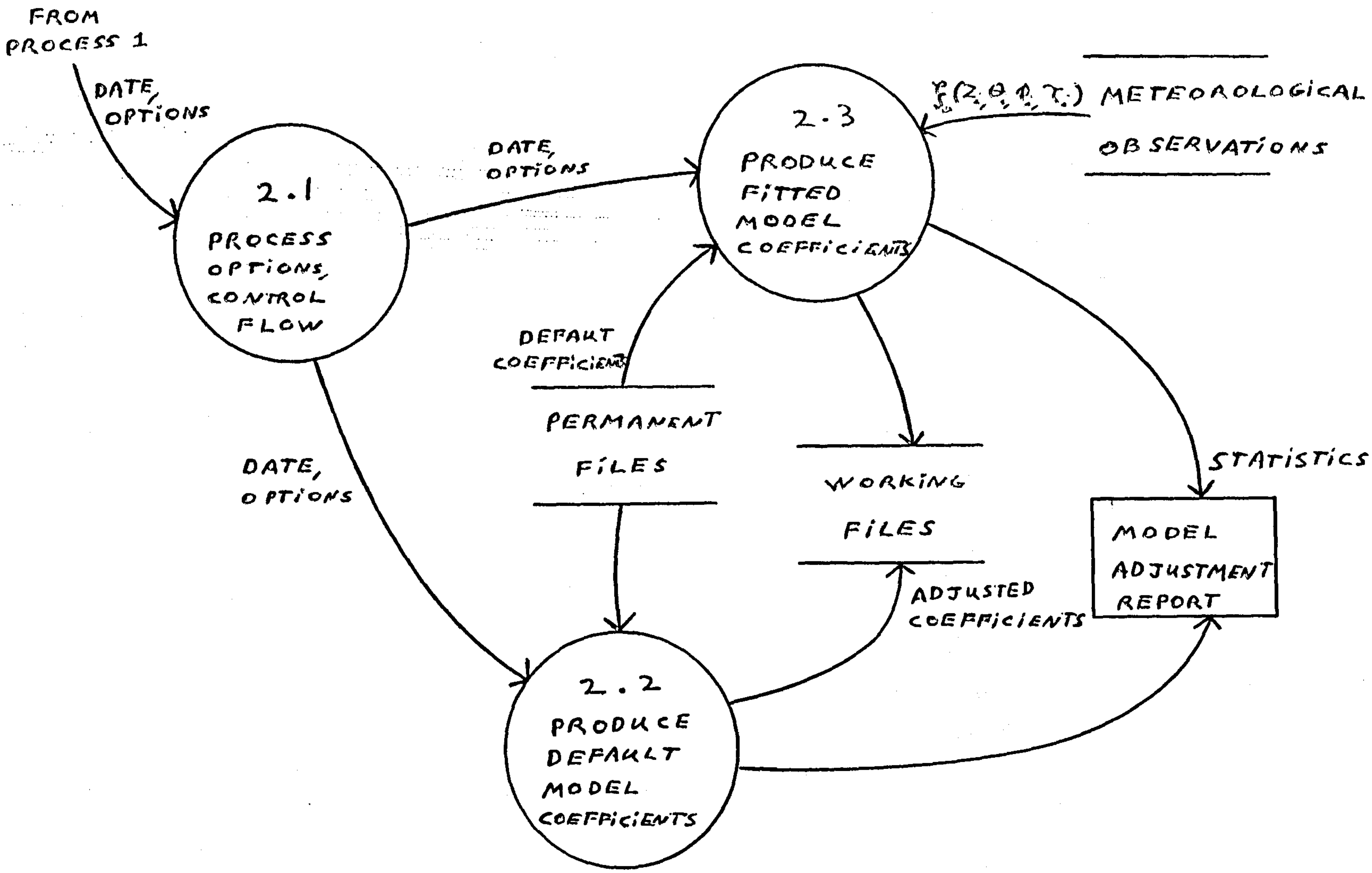

Figure 4-4. Process 2 Details

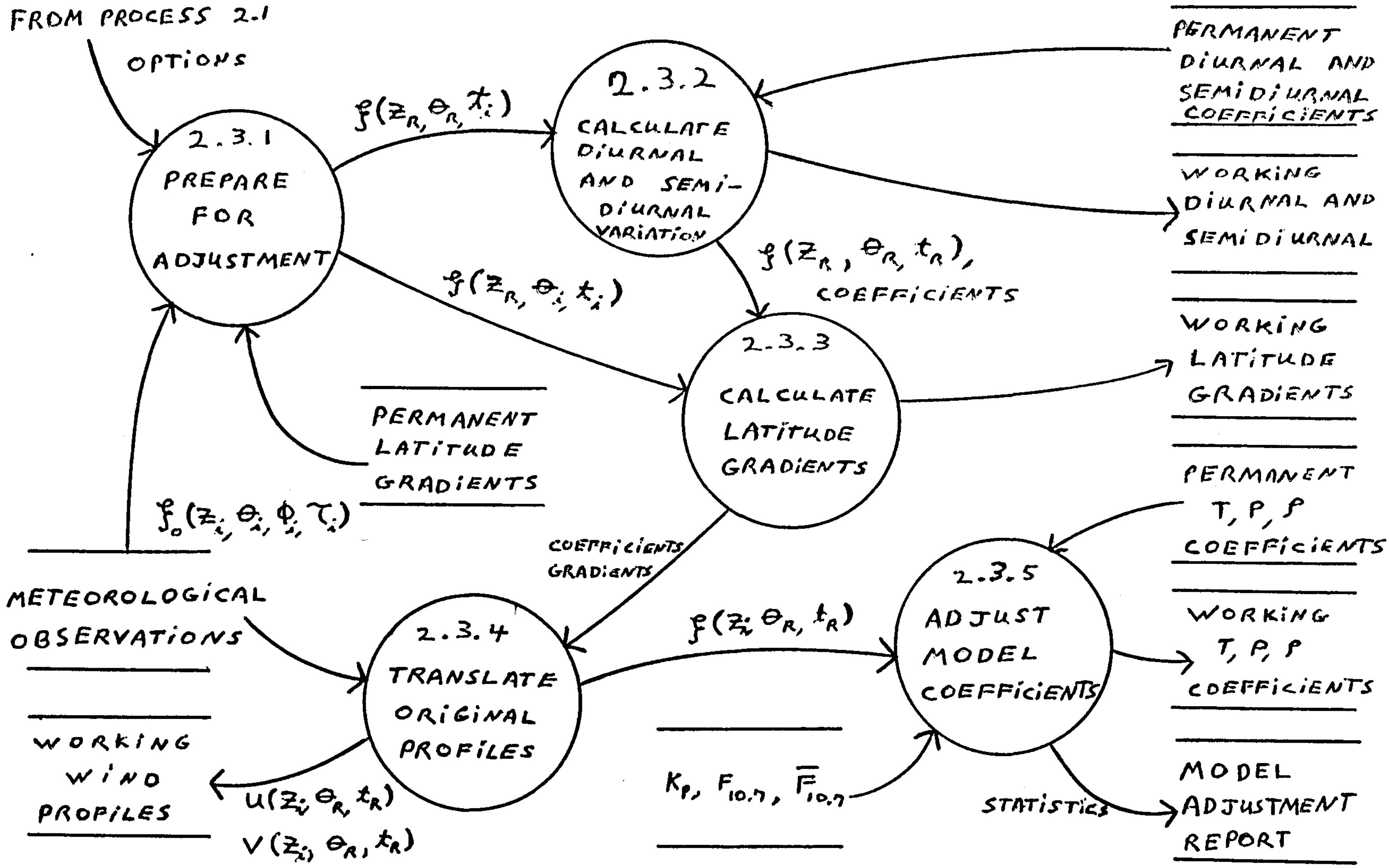

Figure 4-5. Process 2.3 Details

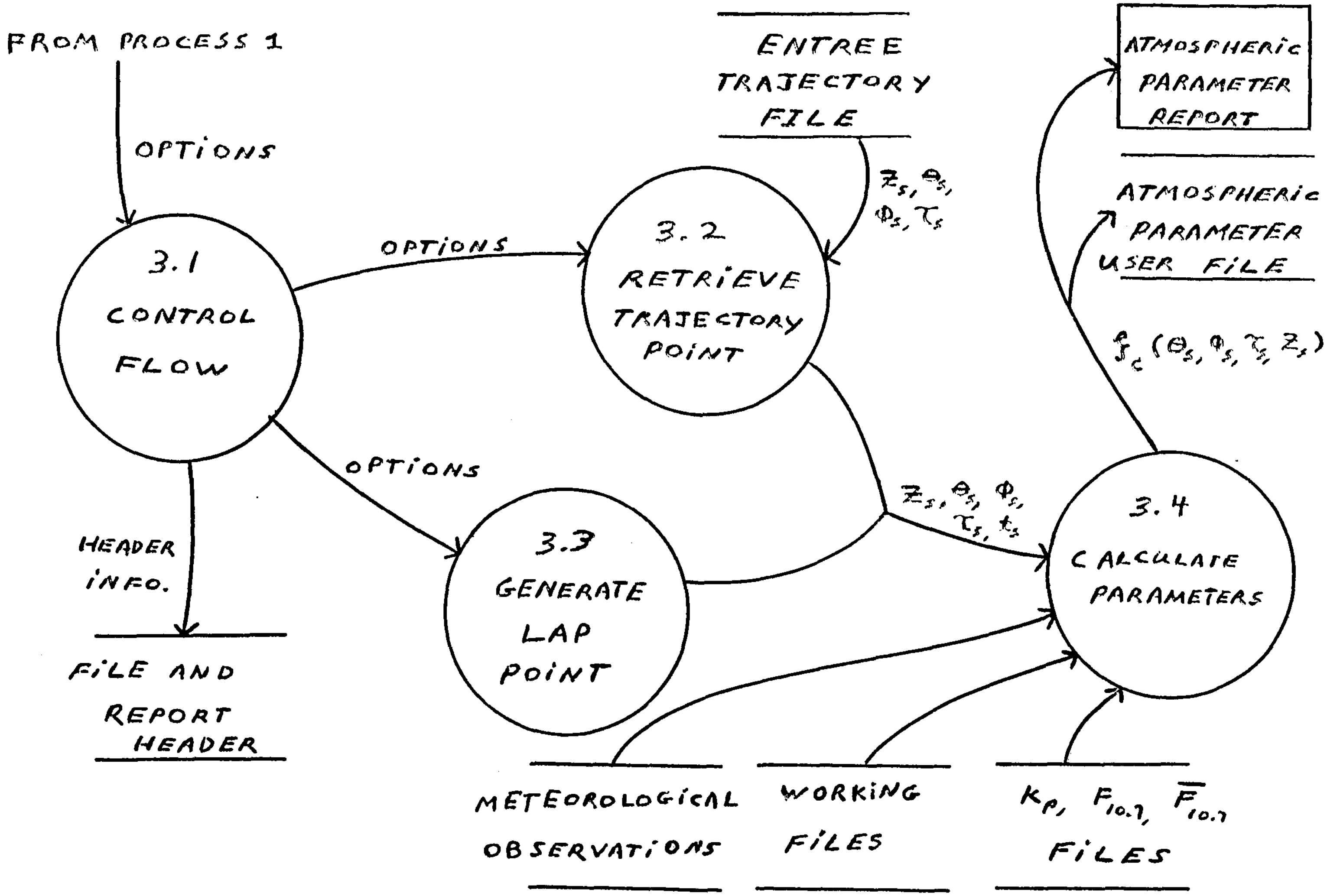

Figure 4-6. Process 3 Details

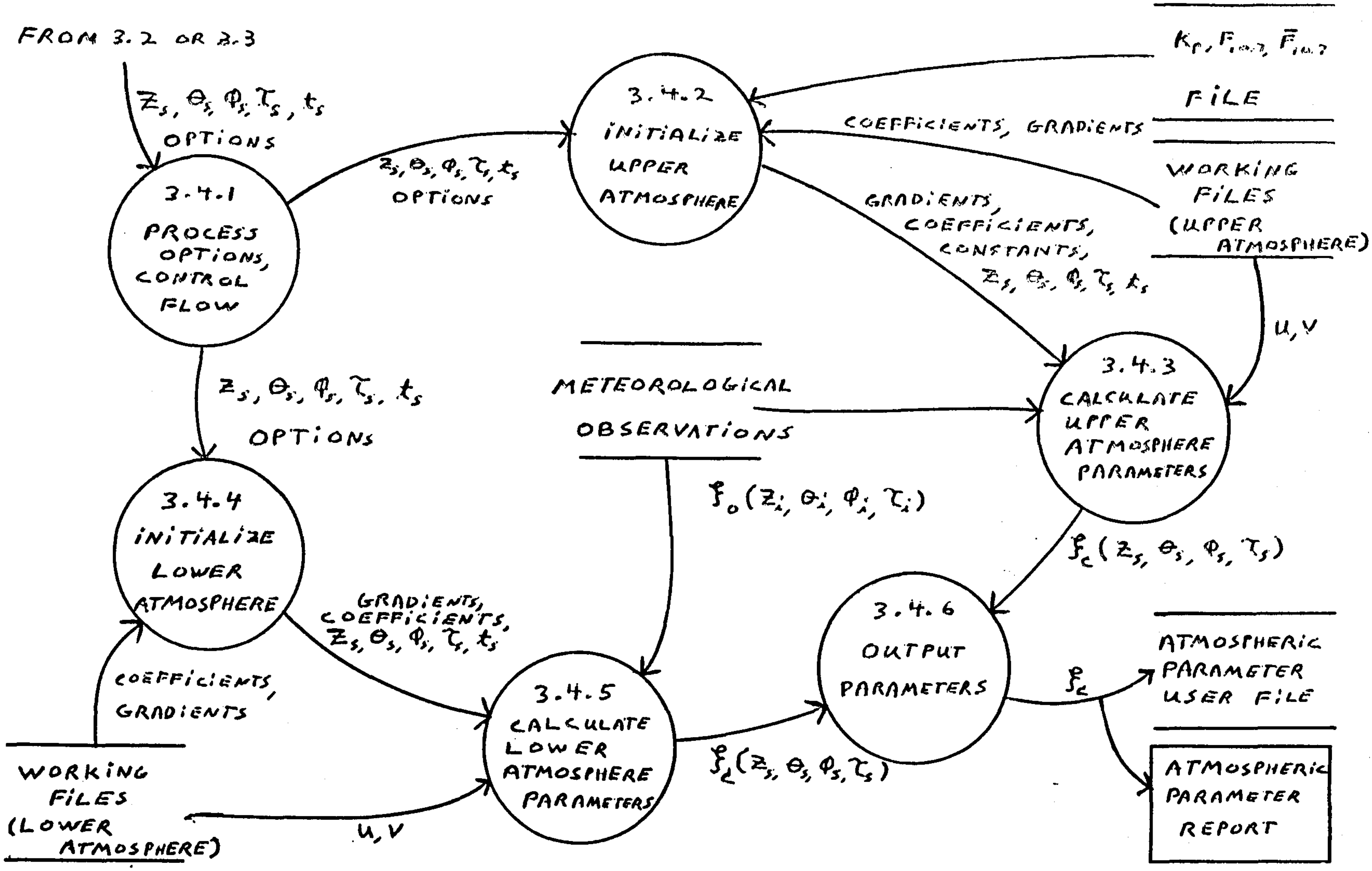

Figure 4-7. Process 3.4 Details

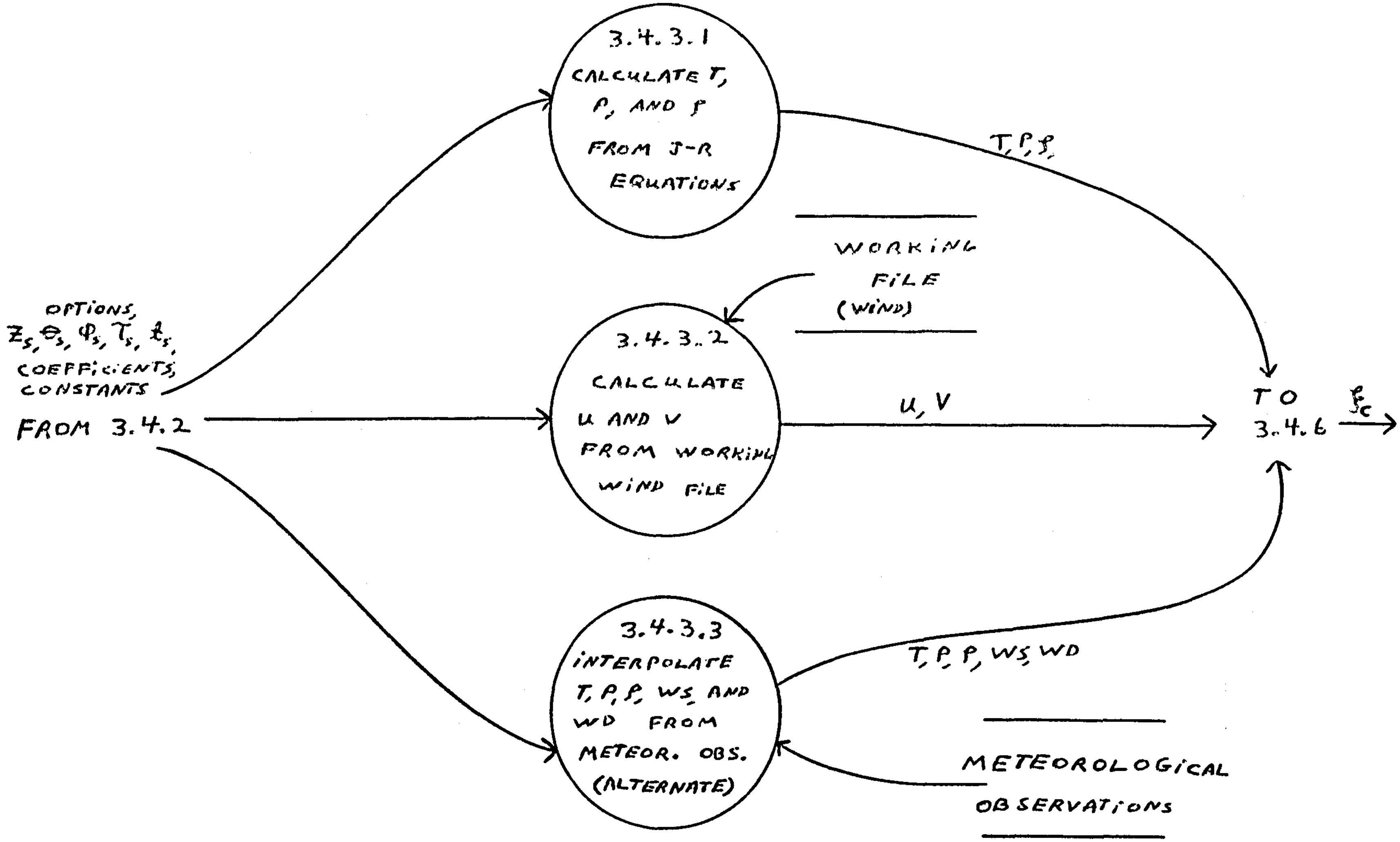

Figure 4-8. Process 3.4.3 Details

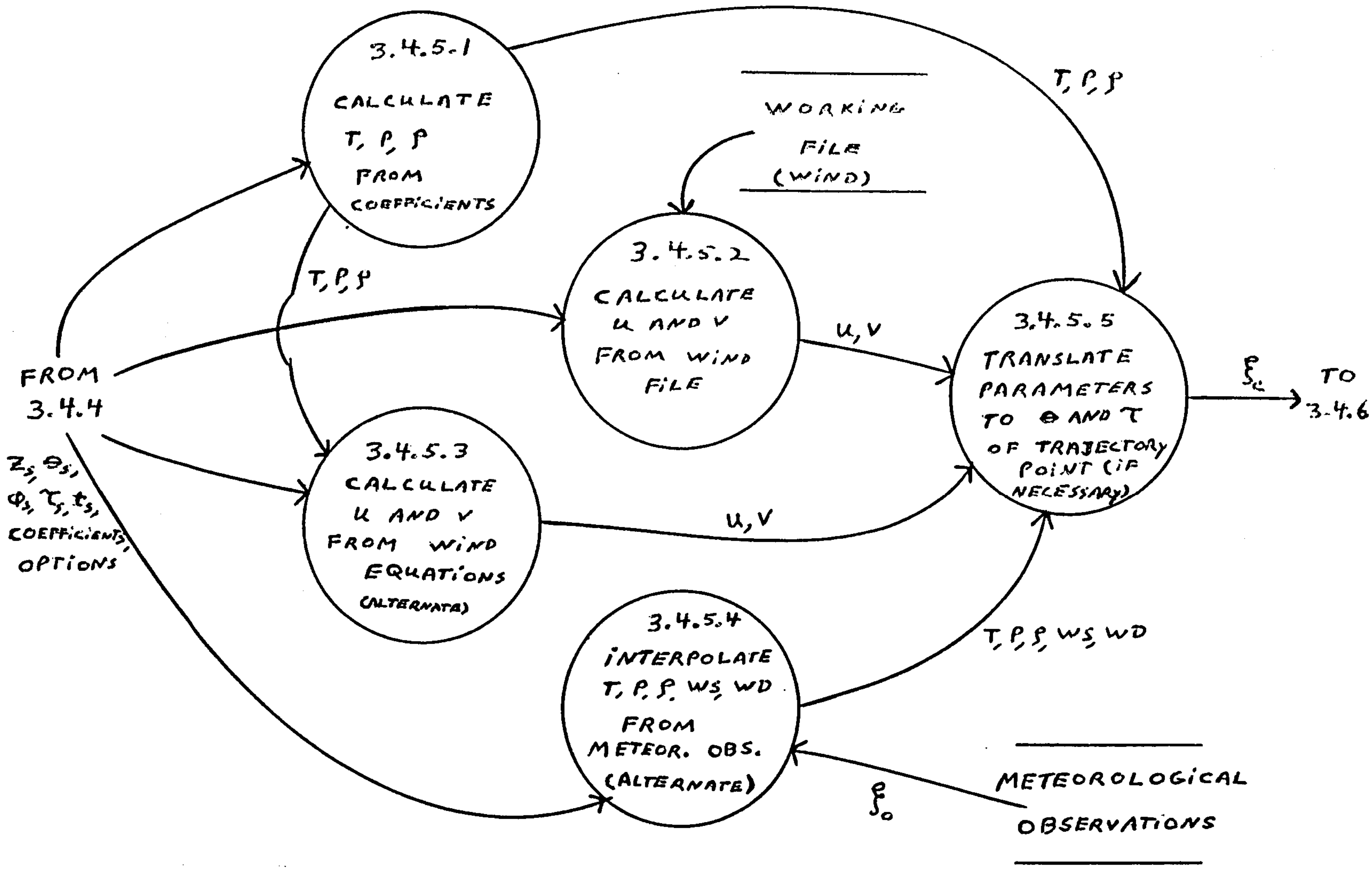

Figure 4-9. Process 3.4.5 Details

<u>COEFFICIENTS</u>

A set of coefficients required by the atmospheric model for determining the altitude profiles of T, P, and ζ, as well as coefficients for determining the diurnal and semidiurnal (D&SD) variations in these quantities and in U and V. Three varieties of coefficients exist in LAIRS:

DEFAULT COEFFICIENTS - Coefficients determined from the default models and stored on permanent files.

ADJUSTED COEFFICIENTS - Coefficients obtained by adjusting the default coefficients on the basis of the input meteorological data. These coefficients are stored on working files. When no meteorological data is available, the set of default coefficients corresponding to the date of the Shuttle's reentry are stored on the working files after Jacchia-Roberts and CIRA merging has been performed.

NEW COEFFICIENTS - Coefficients resulting from permanent file maintenance. Special input is required to produce these coefficients, which are placed on new permanent files. It is not expected that these coefficients will be required on each run.

DATA

The special input required by the permanent file maintenance option.

DATE

The date of the Shuttle reentry input to LAIRS.

HEADER INFORMATION

Information on reentry profile, models used, etc., written to the header of the atmospheric parameter output report and the atmospheric parameter user file.

DATA DICTIONARY

K_p, $F_{10.7}$, $\bar{F}_{10.7}$
Jacchia-Roberts model constants (see symbol definitions)

LATITUDE GRADIENTS
The gradients of T, P, S, U, and V with respect to latitude. These are tabulated for various altitudes and stored on the permanent and working files.

METEOROLOGICAL PROFILES
$\xi_0(Z, \theta_i, \phi, t_i)$ - See PARAMETER SET

MODEL CONSTANTS
Jacchia-Roberts constants

OPTIONS
A set of input options to be supplied by the user on keyword cards, including information such as:

- Which model will be used for parameter calculation (default, adjusted, or interpolation)
- Which type of input trajectory is to be processed (ENTREE Shuttle trajectory, local atmospheric profile "trajectory", or both)
- Which wind model will be used (default, adjusted, interpolation, or analytic)
- Whether permanent file maintenance is desired

PARAMETER SET

A set of atmospheric parameters T, P, ρ, WS, and WD (or T, P, ρ, U, and V) denoted by the symbol ξ. These are either observed or calculated:

$\xi_0(Z, \theta_i, \phi_i, \tau_i)$ - The ith set of observed parameters from the meteorological observations file. It is understood that Z covers the entire altitude range of this set of profiles.

$\xi_c(Z_s, \theta_s, \phi_s, \tau_s)$ - The parameters calculated from the atmospheric model for a point on the Shuttle's trajectory (subscript s). Here Z_s represents only one point, not a profile.

Note: The subscripts on the arguments of ξ are very important. Besides i (ith profile) and s (Shuttle trajectory point), it is possible to have R as a subscript. This denotes the reference point of the model, θ_R and t_R (ϕ and τ are transformed to t), or, in the case of Z, the set of reference altitudes used in computing the diurnal and semidiurnal coefficients and latitude gradients. Thus ξ (Z_R, θ_R, t_R) is a set of profiles at the reference latitude and solar time and computed at the reference altitudes.

DATA DICTIONARY

<u>SHUTTLE TRAJECTORY</u>	The set of points Z_s, θ_s, ϕ_s, τ_s comprising the Shuttle trajectory residing on the ENTREE output trajectory.
<u>STATISTICS</u>	Residuals, standard deviations, observation dispersion information, and other information relating to the model adjustment process
<u>WIND U and V</u>	Tabulations of the wind components U and V for various altitudes. These are stored on the permanent and working files as functions of Z, θ_R, and t_R.

LIST OF SYMBOLS

Symbol	Description
Z	altitude
θ	latitude
ϕ	longitude
τ	time (GMT)
t	solar hour angle (local solar time)
T	temperature
P	pressure
ρ	density
WS	wind speed
WD	wind direction
U	eastward wind component
V	northward wind component
ξ	parameter set consisting of T, P, ρ, WS, and WD, or of T, P, ρ, U, and V ξ_O - observed ξ_C - computed
K_p	geomagnetic index
$F_{10.7}$	10.7-centimeter solar flux
$\overline{F}_{10.7}$	81-day average of 10.7-centimeter flux

PROCESS SPECIFICATION

PROCESS 1: EXECUTIVE CONTROL

1.1 READ the input keyword card deck.

STORE the option flags read from cards in COMMON.

DETERMINE from the option flags whether the user has requested permanent file maintenance.

IF permanent file maintenance has been requested, then

PASS to Process 1.2. On return, proceed.

ELSE no permanent file maintenance has been requested, so

PASS to Process 2 for the building of working files. On return, from Process 2,

PASS to Process 3 for parameter calculation. On return from Process 3,

STOP

1.2 READ the special input supplied by the user for permanent file updates.

UPDATE the permanent file.

WRITE the new permanent files.

RETURN to Process 1.1.

PROCESS 2: MODEL ADJUSTMENT

2.1	DETERMINE	from the option flags whether the default or adjusted model has been requested.
	IF	the default model has been requested, then
		PASS to Process 2.2.
	ELSE	the adjusted model has been requested, so
		PASS to Process 2.3.
2.2	READ	from the permanent files the T, P, ρ, coefficients, the latitude gradients, the diurnal and semidiurnal coefficients, the U and V profiles, and the Jacchia-Roberts constants K_p, $F_{10.7}$, $\overline{F}_{10.7}$ corresponding to the data passed from Process 1.
	WRITE	the retrieved latitude gradients, diurnal and semidiurnal coefficients, and wind U and V profiles to the working files.
	ADJUST	the Jacchia-Roberts model coefficients (which depend on K_p, $F_{10.7}$, and $\overline{F}_{10.7}$) to match the CIRA model coefficients.
	WRITE	the (adjusted) default model coefficients to the working files.
2.3		
2.3.1	DETERMINE	if diurnal, semidiurnal, and latitude variations are to be modeled.
	IF	no such variations are to be modeled,
		PASS to Process 2.3.4.
	ELSE	such variations are to be included, so
	DETERMINE	if more than one profile exists.

IF only one profile exists,

PASS to Process 2.3.2.

ELSE more than one profile exists, so

READ the altitude (Z) values of each profile.

EDIT the profiles with too few Z values.

CONSTRUCT a set of reference Z values (Z_R) from those read.

INTERPOLATE each profile to obtain $\xi(Z_R, \theta_i, \phi_i, \tau_i)$.

TRANSFORM the units of the interpolated profiles to the standard model units (ϕ_i, $\tau_i \rightarrow t_i$).

READ the permanent latitude gradient file for each profile parameter.

TRANSLATE $\xi(Z_R, \theta_i, t_i)$ to $\xi(Z_R, \theta_R, t_i)$ using the retrieved default gradients.

COLLECT statistics on Z_R and $\xi(Z_R, \theta_R, t_i)$ and an original profile $\xi_O(Z_i, \theta_i, \phi_i, t_i)$, and store in COMMON.

PASS to Process 2.3.2.

2.3.2 READ the permanent files to obtain the default diurnal and semidiurnal (D&SD) coefficients.

IF only one set of profiles exists,

WRITE the default D&SD coefficients to the working file.

PASS to Process 2.3.3.

ELSE more than one set of profiles exist, so

SOLVE FOR the D&SD coefficients by the method of Section 3.2.

CHECK the new values against the default values, and set a warning flag if they are too discrepant.

WRITE the new D&SD coefficients to the working file.

COLLECT and store statistics on D&SD fitting.

CONSTRUCT $\xi(Z_R, \theta_R, t_R)$.

PASS $\xi(Z_R, \theta_R, t_R)$ and $\xi(Z_R, \theta_i, t_i)$ to Process 2.3.3.

2.3.3 READ — the permanent latitude gradient file..

IF — only one set of profiles exists,

WRITE the default gradients to the working file.

ELSE — more than one set of profiles exists, so

CALCULATE the new latitude gradients by the method of Section 4.3.

CHECK the new gradients against the old and set a warning flag if they are too discrepant.

WRITE the new gradients to the working file.

PASS — to Process 2.3.4

2.3.4 READ — the original meteorological observation files to obtain the sets of profiles $\xi_0\ (Z_i, \theta_i, \phi_i, \tau_i)$.

IF — D&SD and latitude gradients have not been requested,

MERGE these profiles to obtain the single reference profile set $\xi\ (Z_i, \theta_R, t_R)$ - assume D&SD and latitude gradients are zero.

ELSE — D&SD and latitude gradients have been modeled and are available in COMMON, so

TRANSLATE these profiles to obtain $\overline{\xi(Z_i, \theta_R, t_R)}$ using the D&SD coefficients and the latitude gradients (default values are used when there is only one profile set).

IF — winds have been requested,

WRITE the U and V profiles from the $\overline{\xi(Z_i, \theta_R, t_R)}$ set to the working files.

ELSE — do not write to wind files.

PASS — T, P, ρ from the $\xi(Z_i, \theta_R, t_R)$ set to Process 2.4.

2.3.5 READ — the permanent files to obtain the default model coefficients T, P, ρ for all segments of the atmosphere.

DETERMINE — if any default points must be added to the reference profile, either because of user request or to make the profile complete.

IF — any points must be added, then

CALCULATE the needed points from the default model coefficients and, if the Jacchia-Roberts section is involved, from the K_p, $F_{10.7}$, and $\overline{F}_{10.7}$ values read from the permanent Jacchia-Roberts files.

ADD these points to the reference profile.

ELSE — the profile is complete as is.

SOLVE FOR — the adjustments to the coefficients using the iterative scheme discussed in Section 4.3.

<u>WRITE</u>	the adjusted model coefficients to the working file.
<u>COLLECT</u>	statistics on the model fitting process.
<u>WRITE</u>	the statistics to the model adjustment statistics report.
<u>RETURN</u>	to Process 2.1.

PROCESS 3: ATMOSPHERIC PARAMETER GENERATION

3.1	<u>DETERMINE</u>	from the option flags whether the parameters to be calculated are for an ENTREE trajectory or are for a Local Atmospheric Profile (more than one LAP may be requested; if so, this begins an outer loop).
	<u>IF</u>	an ENTREE profile is requested, then <u>WRITE</u> the Atmospheric Parameter Report header. <u>PASS</u> to Process 3.2
	<u>ELSE</u>	a Local Atmospheric Profile is desired, so <u>WRITE</u> the LAP report header. <u>PASS</u> to Process 3.3.
3.2	<u>READ</u>	a trajectory point from the ENTREE trajectory file.
	<u>PERFORM</u>	any needed transformation of units for this point.
	<u>PASS</u>	to Process 3.4 for parameter calculation for this point.
3.3	<u>CALCULATE</u>	a "trajectory" point for the vertical Local Atmospheric Profile.
	<u>PASS</u>	to Process 3.4 for parameter calculation for this point.
3.4		
3.4.1	<u>DETERMINE</u>	from the trajectory point passed from Process 3.2 (ENTREE) or 3.3 (LAP) whether the upper or lower atmospheric model is required (check value of Z).
	<u>IF</u>	Z lies within the bounds of the upper atmospheric model, then <u>PASS</u> to Process 3.4.2 (upper atmosphere control).

ELSE Z lies within the bounds of the lower atmospheric model, so

PASS to Process 3.4.4 (lower atmospheric control).

3.4.2 DETERMINE if this is the first time the upper atmospheric model has been called for this trajectory.

IF this is the first call, the model needs to be initialized, so

READ the working upper atmospheric files.

STORE the retrieval coefficients in COMMON.

CALCULATE the model constants and store.

ELSE the coefficients have already been retrieved, so proceed.

PASS to Process 3.4.3 for calculation.

3.4.3 DETERMINE if the interpolation model has been requested.

IF the interpolation model has been requested, then (3.4.3.3)

SEARCH for the meteorological profile nearest this point, and retrieve θ and τ for that profile.

INTERPOLATE this profile to find T, P, ρ, WS, and WD for this altitude.

TRANSFORM units of parameters to model standard units.

TRANSLATE the retrieved parameter set in hour angle and latitude to the position of the trajectory point using D&SD coefficients and latitude gradients (if requested).

	ELSE	the Jacchia-Roberts model will be used, so (3.4.3.1)
		CALCULATE the values of T, P, ρ for this trajectory point using the J-R equations, the retrieved model coefficients, and constants.
	IF	Winds U and V have been requested, then (3.4.3.2)
		RETRIEVE U and V from working wind file for this point.
	ELSE	No wind model has been requested, so,
		PROCEED to Process 3.4.6 for output.
3.4.4	DETERMINE	if this is the first time this segment of the lower atmospheric model has been entered on this trajectory.
	IF	this is the first time, the model needs to be initialized so,
		READ the working files for this model segment.
		STORE the retrieved coefficients and gradients in COMMON.
	ELSE	the coefficients for this segment have already been retrieved, so
		PROCEED to 3.4.5 for parameter calculation.
3.4.5	DETERMINE	if the interpolation model has been requested.
	IF	the interpolation model has been requested, then (3.4.5.4)
		SEARCH for the meteorological profile nearest this trajectory point.
		RETRIEVE θ and τ for this profile.
		INTERPOLATE this profile to find T, P, ζ, WS, and WD for this altitude.

TRANSFORM units of parameters to model standard units.

TRANSLATE the retrieved parameter set in hour angle and latitude (t and θ) to the position of the trajectory point, using D&SD coefficients and latitude gradients.

ELSE — the polynomial models have been requested, so

CALCULATE the values of T, P, ρ for the altitude from the retrieved model coefficients.

TRANSLATE the calculated parameters T, P, ρ to the t and θ of the trajectory point using the retrieved D&SD coefficients and latitude gradients (if requested).

DETERMINE — if wind modeling has been requested.

IF — no wind requested,

PROCEED to 3.4.6 for output.

IF — winds from working files requested, then,

RETRIEVE U, V, and latitude gradients for this point from working file (3.4.5.2).

TRANSLATE U and V to the θ and τ of this trajectory point, using retrieved D&SD coefficients and latitude gradients.

ELSE — analytic wind model has been requested, so

CALCULATE U and V from the wind equation, using T, P, and ρ previously calculated and gradients previously retrieved from working file.

PROCEED to 3.4.6 for output.

3.4.6 WRITE the values of the trajectory point (Z, θ, ϕ, t) and the corresponding calculated parameters (T, P, ρ, and horizontal wind components) to the Atmospheric Parameter Report, or the Local Atmospheric Profile Report. Also write to the user file if this is an ENTREE, not a LAP, trajectory.

DETERMINE if the point just processed is the last point on the LAP or ENTREE trajectory.

IF this was the last point, this particular profile is completed, so

RETURN control to Process 3.1 (atmospheric model executive) to begin processing the next requested ENTREE or LAP trajectory.

ELSE more points on this trajectory remain to be processed, so

RETURN control to Process 3.2 (if this is an ENTREE trajectory) or Process 3.3 (if this is a LAP) to process the next trajectory point.

4.6 SOFTWARE CONSTRAINTS

4.6.1 EXECUTION ENVIRONMENT

The Langley Atmospheric Information Retrieval System will be designed to operate on the CDC 6000 and Cyber series computers at the Langley Research Center at Hampton, Virginia. The upper limit on the main memory core requirements should be approximately 200K.

The language of LAIRS will be high-level FORTRAN consistent with LaRC coding standards. No assembler code will be written. No routines will contain multiple entry or exit points, nor will they contain assigned variables. The use of GO TO statements will be held to a minimum. All COMMON blocks will be as small and as specialized as possible; there will be no use of blank, global COMMON. Subroutines of unreasonable length will not be permitted.

4.6.2 MAINTENANCE CONSIDERATIONS

The LAIRS development will utilize modular software throughout, so that new capabilities can be easily added to the system. An attempt will be made to foresee possible areas of future enhancement and to provide appropriate dummy subroutines or, if dummy routines are not feasible, easily alterable code.

The model adjustment software will be designed to allow the user to rebuild the permanent files should superior default data become available. The Jacchia-Roberts, K_p, $F_{10.7}$, and $\bar{F}_{10.7}$ files will require periodic updating, which may be accomplished by software available from CSC.

Consistent subroutine and COMMON block documentation will be stressed at all stages of development. This documentation, combined with the modular structure of the system and the coding standards elaborated upon in Section 4.6.1, will insure that LAIRS is an easily maintainable, upgradable system.

REFERENCES

1. R. A. Minzer, K. W. Champion, and H. Pond, "The 1959 ARDC Model Atmosphere," Air Force Surveys in Geophysics, no. 115, Air Force Cambridge Research Center, 1959
2. Committee on Extension of Standard Atmosphere, U. S. Standard Atmosphere, 1962. Washington, D. C.: Government Printing Office, 1962
3. --, U. S. Standard Atmosphere, 1976. Washington, D. C.: Government Printing Office, 1976
4. COSPAR Working Group IV, COSPAR International Reference Atmosphere 1965. Amsterdam: North-Holland Publishing Co., 1965
5. --, COSPAR International Reference Atmosphere 1972. Berlin: Akademie-Verlag, 1972
6. Somerville et al., "The GISS Model of the Global Atmosphere," Journal of Atmospheric Sciences, 1974, vol. 31, no. 1, pp. 84-117
7. National Aeronautics and Space Administration, TM X-64970, Hot, Cold, and Annual Reference Atmospheres for Edwards Air Force Base (1975 Version), D. L. Johnson, 1975
8. H. R. Compton, R. C. Blanchard, and D. Walberg, "An Experiment for Shuttle Aerodynamic Force Coefficient Determination From Inflight Dynamical and Atmospheric Measurements," (paper presented at the AIAA 10th Aerodynamic Testing Conference (Paper No. 78-795), San Diego, California, 1978)
9. L. G. Jacchia, "Recent Atmospheric Models and Improvement in Progress," in COSPAR Space Research XIX, pp. 179-192. Berlin: Akademie-Verlag, 1979
10. G. P. Newton and H. G. Mayr, "Diurnal and Semidiurnal Nitrogen Density and Temperature Variations From Thermosphere Probe Measurements," Journal of Geophysical Research, 1973, vol. 78, no. 25, pp. 5687-5692
11. S. L. Valley (editor), Handbook of Geophysics. New York: Macmillan, 1965
12. I. Harris and W. Priester, "Time-Dependent Structure of the Upper Atmosphere," Journal of the Atmospheric Sciences, 1962, vol. 19, no. 4, pp. 286-301
13. Smithsonian Astrophysical Observatory, Special Report No. 332, Revised Static Models of the Thermosphere and Exosphere With Empirical Temperature Profiles, L. G. Jacchia, 1971

14. C. H. Eckart, Hydrodynamics of Oceans and Atmospheres. New York: Pergamon Press, 1960

15. Goddard Space Flight Center, X-582-76-77, Mathematical Theory of the Goddard Trajectory Determination System, J. O. Cappellari, Jr., C. E. Velez, and A. J. Fuchs (editors), 1976

16. D. L. Dowd and B. D. Tapley, "Density Models for the Upper Atmosphere," (paper presented at GSFC Flight Mechanics Symposium, Greenbelt, Maryland, October 1977 (NASA Conference Publication 2050, pp. 38-78))

17. L. G. Jacchia and J. Slowey, "The Shape and the Location of the Diurnal Bulge in the Upper Atmosphere" in Space Research VII. Amsterdam: North-Holland Publishing Co., 1967

18. E. R. Roberts, Jr., "An Analytical Model for Upper Atmosphere Densities Based Upon Jacchia's 1970 Models," Celestial Mechanics, 1971, vol. 4, no. 3, pp. 368-377

19. Smithsonian Astrophysical Observatory, Special Report No. 375, Thermosphere Temperature, Density, and Composition: New Models, L. G. Jacchia, 1971

20. A. E. Hedin et al., "A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data" (MSIS 1. N_2 Density and Temperature and MSIS 2. Composition), Journal of Geophysical Research, 1977, vol. 82, no. 16, pp. 2139-2156

21. P. E. Elyasberg, B. V. Kugaenco, V. M. Synitsyn, and M. I. Vaiskovsky, "Upper Atmosphere Density Determination From the Cosmos Satellite Deceleration Results" in Space Research XII. Berlin: Akademie-Verlag, 1972

22. Smithsonian Astrophysical Observatory, Special Report No. 313, New Static Models of the Thermosphere and Exosphere With Empirical Temperature Profiles, L. G. Jacchia, 1970

23. J. W. Chamberlain, Theory of Planetary Atmospheres. New York: Academic Press, 1978

24. J. A. Dutton, The Ceaseless Wind, New York: McGraw-Hill, 1976

25. T. Beer and Kucheraway, The Aerospace Environment. New York: Crane, Russak, and Co., 1976

26. J. L. Fellous, R. Bernard, M. Glass, M. Massebent, and A. Spizzichivo, "A Study of the Variations of Atmospheric Tides in the Meteor Zone," The Journal of Atmospheric and Terrestrial Physics, 1975, vol. 37, pp.1511-1524

27. TRW, 79.6435.14-019, OFT Ascent/Descent Ancillary Data Products Program Input/Output Interface Control Document, R. D. Martz, October 1, 1979

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-159374		

4. Title and Subtitle	5. Report Date
EVALUATION OF ATMOSPHERIC DENSITY MODELS AND PRELIMINARY FUNCTIONAL SPECIFICATIONS FOR THE LANGLEY ATMOSPHERIC INFORMATION RETRIEVAL SYSTEM (LAIRS)	September 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
T. Lee and D. E. Boland, Jr.	CSC/TM-80/6240
	10. Work Unit No.
9. Performing Organization Name and Address	
Computer Sciences Corporation System Sciences Division 8728 Colesville Road Silver Spring, MD 20910	11. Contract or Grant No. NAS1-15663
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code 506-51-33-01

15. Supplementary Notes

Langley technical monitor: Joseph M. Price

16. Abstract

This document presents the results of an extensive survey and comparative evaluation of current atmosphere and wind models for inclusion in the Langley Atmospheric Information Retrieval System (LAIRS). It includes recommended models for use in LAIRS, estimated accuracies for the recommended models, and functional specifications for the development of LAIRS.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Atmospheric model Wind model Meteorology	Unclassified - Unlimited Subject Category 47

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	119	A06

For sale by the National Technical Information Service, Springfield, Virginia 22161

End of Document